White light interferometry on 3D opal based photonic crystals

J. F. Galisteo-López[a)], M. Galli[b)], M. Patrini[b)], L. C. Andreani[b)], and C. López[a)]
[a)]Instituto de Ciencias de Materiales de Madrid (CSIC), Cantoblanco 28049, Madrid, Spain
[b)]Dipartimento di Fisica "A. Volta", Università di Pavia, Via Bassi 6, I-27100 Pavia, Italy

White light interferometry in the time domain is a powerful technique that permits obtaining phase sensitive information from photonic crystals (PhCs)[1] which is not easily provided by optical characterisation methods like reflectance and transmittance. With this technique we have measured the phase delay introduced by 3D opal based PhCs along the ΓL direction in reciprocal space for different crystal configurations (lattice parameter and sample thickness).

From the phase delay, an effective refractive index as well as group velocity is extracted. In the energy region of the L-pseudogap we observe the development of a spectral interval with anomalous dispersion for the refractive index. The group velocity shows pronounced slowing down at the band edge and becomes superluminal in the photonic gap. The behaviour with crystal parameters is discussed.

The wide spectral range provided by the technique allows extending the study into the high energy region where higher order diffractions both by {111} planes and other families of planes take place.[2] Preliminary results in this spectral range are presented.

[1] M. Galli, *et. al*, *Phys. Rev. B*, **69**, 115107 (2004).
[2] J. F. Galisteo-López and C. López, *Rev. B*, **70**, 035108 (2004).

Full transmission through perfect-metal subwavelength hole arrays

F. J. García de Abajo,[1] R. Gómez Medina,[1] J. J. Sáenz,[2 1] Donostia International Physics Center and Centro Mixto CSIC-UPV/EHU, San Sebastián, Spain, [2] Department of Condensed Matter, Universidad Autónoma de Madrid, Spain.

Light transmission through 2D subwavelength hole arrays in perfect metal films is shown to be complete (100%) at some resonant wavelengths even for arbitrarily narrow holes. Conversely, the reflection on a 2D planar array of non-absorbing scatterers is shown to be complete at some wavelengths regardless how weak the scatterers are. These results are proven analytically and corroborated by rigorous numerical solution of Maxwell's equations. This work supports the central role played by dynamical diffraction during light transmission through subwavelength hole arrays and it provides a systematics to analyze more complex geometries and many of the features observed in connection with transmission through hole arrays.

Using dispersion relationships for finite length PhC waveguides characterisation

J. García, P. Sanchis, and J. Martí,
Valencia Nanophotonics Technology Center, Universidad Politécnica de Valencia, Camino de Vera s/n, 46022 Valencia, Spain

A numerical procedure for characterise finite length PhC waveguides is presented. This characterisation is achieved by using 1) the dispersion relationship of the guided mode for the infinite waveguide and 2) the transmission and reflection coefficients at the input and output interfaces of this waveguide [1]. This procedure allows achieving very accurate results when propagating pulses in these finite length waveguides (even at the band edge), with a huge time and resources saving compared to FDTD simulations.

This procedure will be used to analyze the influence of the parameters that define the waveguide (such as its length or its termination at the interfaces) over the total output pulse shape and parameters. The main effect analyzed in this work will be the effect of the non-perfect coupling at the access ports over the output pulse.

[1] P. Sanchis, P. Bienstman, B. Luyssaert, R. Baets, and J. Martí, *IEEE J. Quantum Electron.*, **40**, pp. 541-550 (2004).

Intermodal dispersion conpensation in a PhC directional coupler.

F. Cuesta-Soto, B. García-Baños, A. Håkanson, J. García, P. Sanchis and J. Martí, Valencia Nanophotonics Technology Center, Camino de Vera s/n, Valencia, Spain.

Photonic crystal directional couplers (PhCDC) are of general interest due to its compactness and high confinement of light [1]. However big intermodal dispersion can be found, specially near the band edge of one of the supermodes where the theoretical group velocity vanishes. This leads to a constraint in the bandwidth of a pulse travelling through it.

In this study, a novel intermodal dispersion compensator is presented. This compensator inverts the intermodal dispersion of a PhCDC by changing the relative dispersion relation of the supermodes of the structure. This is achieved by increasing the distance between the guides of the device [2]. Additionally, two mandatory requirements are fullfilled. The slope of the coupling coefficient has the same sign as in the PhCDC; and the coupling between its normal supermodes and those of the PhCDC are balanced. The last requirement has been achieved by introducing a small coupling area that has been optimized by a genetic algorithm.

[1] A. Martínez, F. Cuesta and J. Martí, *IEEE Photon. Tech. Letters*, **15**, 5 (2003).

[2] C. M. Sterke, L. C. Botten and A. A. Asatryan, T. P. White and R. C. McPhedran; *Optics Letters,* ***29,*** 12 (2004).

Effects of the lattice orientation and the interface termination on negative refraction in 2D photonic crystals

Alejandro Martínez and Javier Martí,
Valencia Nanophotonics Technology Center, Universidad Politécnica de Valencia
Campus del Camino de Vera, 46022 Valencia (Spain)

Negative refraction at the interface between air and a 2D square photonic crystal (PhC) at frequencies corresponding to the second band is analysed by means of equifrequency contour (EFC) diagrams and FDTD simulations. Several lattice orientations inside the slab giving rise to different slab terminations are considered to observe the influence of the lattice and the termination over the EM propagation. In principle, from the EFC analysis it could be established that if the EFC has a rounded shape and its radius decreases with frequency, the PhC should behave as a refractive medium with a negative effective index. However, we find that these conditions are not sufficient for the PhC to behave as a negative refractive medium. EM propagation inside the PhC is highly sensitive to the lattice orientation and the interface periodicity. It can be stated that a negative refractionlike behavior can only be observed when the interface is periodic and the mode symmetries of the external plane wave and the Bloch wave inside the PhC are matched. Even under this assumption, the Snell's law is not satisfied if the interface is not properly selected because the EFC retains a slight square-like shape even for frequencies near the bandgap. In addition, when the Snell's law is met the Goos-Hänchen effect for a finite slab has to be considered to obtain the effective index of refraction.

Diffraction and high-energy features in three-dimensional photonic crystals

F. García-Santamaría[1], J. F. Galisteo-López[2], C. López[2], and P. V. Braun[1]

[1]Department of Materials Science and Engineering, Frederick Seitz Materials Research Laboratory and Beckman Institute,
University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

[2]Instituto de Ciencia de Materiales de Madrid, C/ Sor Juana Inés de la Cruz 3, 28049-Madrid, Spain

Diffraction phenomena in three-dimensional (3D) photonic crystals (Fig. 1) present a number of issues such as: surface or bulk effect; is the 2D grating equation sufficient; the symmetry the pattern should have; their impact on transmission and reflectance spectra.

Here we provide a band structure based interpretation of the diffraction observed in 3D photonic crystals. Qualitative and quantitative information about the patterns is obtained in a simple manner from the band structure. Our conclusions and experimental results explain phenomena occurring at frequencies above the first stop band that were previously not properly interpreted. Optical features observed in transmission spectra from opaline photonic crystals are now viewed under a new light by relating them to the diffraction phenomena. We also observe an intriguing change in the diffraction pattern symmetry when the photonic crystal dielectric contrast is modified (Fig. 1c).

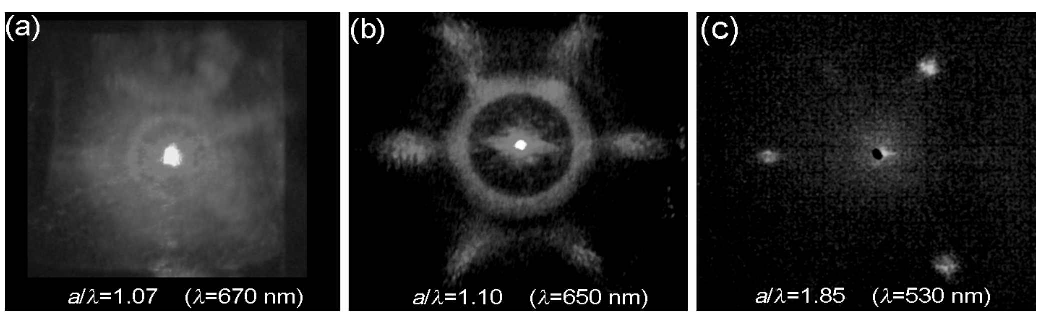


Figure 1. (a, b) Diffraction patterns from opals of 505 nm diameter polystyrene spheres in air. (c) Diffraction pattern from an opal of 695 nm polystyrene microspheres with 70% of the pore volume loaded with SiO_2.

Photonic Crystals for Compact Gas Sensors

T.M. Geppert[1], D. Pergande[2], A.v. Rhein[2], S.L. Schweizer[2] and R.B. Wehrspohn[2]
[1]Max Planck Institute of Microstructure Physics, Weinberg 2, 06120 Halle, Germany,
[2]University Paderborn, Dep. Physics, Warburgerstr. 100, 33098 Paderborn, Germany

The band structure of photonic crystals (PhCs) strongly alters the behaviour of light within such periodically structured dielectrics. Properly designed PhCs should allow the realization of a new kind of compact spectroscopic gas sensors.

Its working principle is built on utilizing the low group velocity v_g of light in flat parts of the photonic band structure. This low v_g increases the effective interaction between the light and the gas. It therefore allows to decrease the size of the interaction volume and along with it the total size of a spectroscopic gas sensor. However, the low v_g also leads to a high reflection at the interface air/PhC due to mode and group velocity mismatch. We have developed a simple design adapted to narrow band spectroscopy that allows for a transmission of more than 90% in spectral regions with low v_g. It is based on a thin, unstructured layer of the dielectric making up the PhC at the air/PhC interfaces of a two-dimensional PhC. Numerical simulations by FEM-methods incorporating gas absorption and the impedance matching layer show that a reduction of the interaction volume by a factor of 25 to 30 is possible under realistic conditions.

We realised such structures by using macroporous silicon technology. More than 400µm deep pores with a lattice constant of 4.2µm have been realised. These deep silicon structures were partially open on both sides to allow for a certain gas flow through the structures. Transmission and reflection measurements of such structures with a length of a few mm up to one cm have been tested optically using either an FT-IR spectrometer or a QCL-Laser at the target frequency of ~10µm.

Disorder-induced losses in photonic crystal waveguides

D. Gerace and L.C. Andreani
INFM and Dipartimento di Fisica "A. Volta", Università di Pavia, I-27100 Pavia, Italy

Photonic modes lying below the light line in photonic crystal (PhC) slabs are truly guided and their propagation losses follow from the presence of structural disorder. In this work, a model for disorder-induced losses in PhC slabs is studied. The model consists of assuming a random distribution of hole (or pillar) radii, described by a Gaussian function. The model is applied to the calculation of propagation losses in various high-index contrast PhC slabs containing line-defect waveguides. In particular, we consider W1-type waveguides (i.e., a missing row of holes along the ΓK direction of the triangular lattice with lattice constant *a*) in a high-index membrane and show that propagation losses are substantially reduced by increasing the channel width from $w=w_0\equiv\sqrt{3}a$ (W1) to $w=1.5w_0$ (W1.5 waveguide), while maintaining a monomode propagation region. We also consider linear waveguides in the square lattice of dielectric pillars and compare the propagation losses with those measured in recent experiments [M. Tokushima et al., APL 84, 4298 (2004)]. A comparison between the roles of disorder in hole and pillar lattices is also discussed.

Synthesis, characterization and modelling of direct and inverse opals

F. Giorgis[1], C. Ricciardi[1], M. Quaglio[1], F. Geobaldo[2], L. Pallavidino[2], M. Galli[3], D. Bajoni[3], A. Balestreri[3], L.C. Andreani[3]
[1]Dept. of Physics, Polytechnical University of Torino, I –10129, Turin, Italy.
[2]Dept. of Material Science and Chemical Engineering, Polytechnical University of Torino, C.so Duca degli Abruzzi 24, I-10129 Turin, Italy.
[3]Dept. of Physics “A. Volta”, University of Pavia, Via Bassi 6, 27100 Pavia, Italy

We present results on the synthesis of Silica-based direct opals obtained by dip-coating technique starting from nanospheres with controlled diameter ranging from 150 nm up to 700 nm. The templates were infiltrated with Silicon by Low Pressure Chemical Vapour Deposition and the Silica matrix was removed by Reactive Ion Etching combined with HF etching, obtaining Si-based inverted opals. The quality of the 3D structures was checked by Raman spectroscopy, Atomic Force and Scanning Electron Microscopies, carefully analysing the presence of cracking and stacking faults. Optical characterizations were performed by stationary photoluminescence for the analysis of the influence of the PBG on the spontaneous emission and variable-angle reflectance aimed at obtaining the photonic bands. The optical measurements on direct and Silicon-infiltrated opals show the formation of PBGs, which tend to evolve towards an angular-independent, complete PBG for the inverse opal structure. Moreover, they show spectral features related to diffraction effects taking place within the photonic crystal. The interpretation is supported by calculations of photonic bands, as well as reflection and diffraction spectra, for the investigated structures.

Second harmonic generation in amorphous silicon nitride doubly resonant microcavities with periodic dielectric mirrors

S. Lettieri[1], F. Gesuele[1], P. Maddalena[1], M. Liscidini[2], L.C. Andreani[2], C. Ricciardi[3], V. Ballarini[3], F. Giorgis[3]

[1]CRS Coherentia and Physics Department, University of Napoli ‘Federico II’, Via Cintia, I-80126 Napoli, Italy

[2]Dept. of Physics “A. Volta”, University of Pavia, Via Bassi 6, I-27100 Pavia, Italy

[3]Dept. of Physics, Polytechnical University of Torino, I–10129, Turin, Italy.

Optical second harmonic generation (SHG) in planar microcavities (MCs) is a subject of growing interest. In the recent past, we demonstrated the possibility of fabricating MCs entirely based on amorphous silicon nitride (a-SiN:H) [1]. Later, SHG in silicon nitride microcavities with the pump wave being resonant with the Fabry-Pérot mode has been demonstrated [2]. These systems can be viewed as one-dimensional photonic crystals with defect cavity layers.

In this work, starting from theoretical studies [3], we report on the first realization of a doubly resonant microcavity based on periodical mirrors [4]. Differently from other proposed lay-outs with non-periodic multilayers [5], with the present microcavity design based on photonic crystal concepts the resonant features are robust with respect to moderate deviations of the layer thicknesses. Such deviations (plausible in realistic growth performed by MBE or PECVD) produce at the most a resonance shift, which can be compensated by tuning the angle of incidence and the polarizations of input and output beams.

SHG with simultaneous resonance at the pump and harmonic waves is demonstrated at finite values of the angle of incidence. The results are in good agreement with a theoretical calculation of the harmonic generation process based on a nonlinear polarization localized at the interfaces between different centrosymmetric layers.

[1] F. Giorgis, Appl. Phys. Lett. **77**, 522 (2000)

[2] S. Lettieri, S. Di Finizio, P. Maddalena, V. Ballarini, F. Giorgis, Appl. Phys. Lett.**81**, 4706 (2002)

[3] M. Liscidini, L. C. Andreani, Appl. Phys. Lett. **85**, 1883 (2004)

[4] S. Lettieri, F. Gesuele, P. Maddalena, M. Liscidini, L.C. Andreani, C. Ricciardi, V. Ballarini, F. Giorgis, to be published

[5] C. Simonneau, J. P. Debray, J. C. Harmand, P. Vidakovic, D. J. Lovering, and J. A. Levenson, Opt. Lett. **22**, 1775 (1997).

Micro-fabrication and characterization of composite meta-materials designed for 100 GHz operation regime

M. Gökkavas[1], K. Güven[2], and E. Ozbay[1,2]

[1]Nanotechnology Research Center, Bilkent University, 06800 Ankara, TURKEY

[2]Department of Physics, Bilkent University, 06800 Ankara, TURKEY

We report the micro-fabrication and measured transmission spectra of composite meta-material (CMM) structures consisting of periodically stacked split-ring resonator (SRR) and wire layers particularly designed for operation around 100 GHz. The layers forming the meta-material are fabricated on glass substrates by using standard photolithography, metal deposition, and lift-off techniques. By employing an experimental setup constructed around a network analyzer, two microwave sources, a frequency multiplier, and a mixer, the transmission spectra of SRR-only, wire-only, and CMM structures are measured and reported in the 75-120 GHz frequency range. The SRR-only structure displays a $\mu<0$ transmission dip around 100 GHz, and the wire-only structure displays a stop band which extends up to ~115 GHz. We will be reporting our ongoing efforts towards obtaining a CMM transmission band in the anticipated $\mu<0$, $\varepsilon<0$ regime.

Low frequency surface plasmons on periodic semiconductor structures

J. Gómez Rivas and P. Haring Bolivar
Institute of High Frequency and Quantum Electronics, University of Siegen, D-57068 Siegen, Germany.

J.A. Sánchez-Gil,
Instituto de Estructura de la Materia, Consejo Superior de Investigaciones Científicas, Serrano 121, 28006 Madrid, Spain.

Surface plasmon polaritons SPPs are electromagnetic waves coupled to the oscillation of free charges on the surface of a metal. The large electromagnetic field at the metal surface and the possibility to guide waves beyond the diffraction limit has lead to an extraordinary interest in the field of surface plasmon optics or plasmonics [1]. This research has focused mainly at optical and near-infrared frequencies. The huge permittivity of metals at low frequencies (THz and microwaves) leads to weakly bounded SPPs to the surface, limiting the usefulness of low frequency plasmonics. We have recently demonstrated that this limitation can be easily overcome by using doped semiconductors instead of metals [2]. Semiconductors have a permittivity at low frequencies similar to that of metals in the visible, thereby making possible to excite and propagate low frequency SPPs.

We have investigated experimentally and theoretically the transmission of SPPs through gratings of grooves structured in doped Si with different doping concentrations. For the experiments we use THz time-domain spectroscopy, a technique that allows the direct measure of the amplitude and the phase of ultrashort THz pulses. From the analysis of the amplitude we see that Bragg scattering of SPPs by the periodic structure leads to the formation of a stop-gap, or a frequency range where the transmission is virtually suppressed. From the phase analysis important information such as the phase and the group velocities of the SPPs can be obtained. We observe a strong reduction of the group velocity at the edge of the stop gap due to the resonant scattering.

[1] W.L. Barnes, A. Dereux, and T.W. Ebbesen, *Surface plasmon subwavelength optics*, Nature **424**, 824 (2003).
[2] J. Gómez Rivas, M. Kuttge, P. Haring Bolivar, H. Kurz and J.A. Sánchez-Gil, *Propagation of surface plasmon polaritons on semiconductor gratings*, Phys. Rev. Lett. **93**, 256804 (2004).

Efficient High-drop Channel-Drop Filters with Photonic Crystal Slabs

A. Gomyo, J. Ushida, and M. Shirane
NEC Corp., 34, Miyukigaoka, Tsukuba, Ibaraki, 305-8501, Japan

In-plane channel-drop optical filters (CDFs), which are based on 2-D photonic crystal (PCs) slabs, are effective in wavelength division multiplexing for photonic networks. We have developed an efficient high-drop CDF using PC slabs, and we confirmed the CDF's operation at a wavelength around 1600 nm.

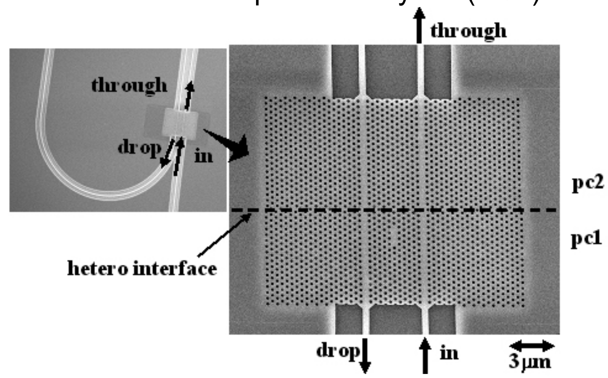


Fig. 1 SEM images of CDF device

We fabricated a PC-slab CDF with a hexagonal-lattice air hole and a silicon-on-insulator substrate (Fig. 1). It had a single defect cavity and a hetero-interface as a highly reflective interface. The spectrum from the drop-port showed a sharp peak at 1600 nm. The peak power ratio of the drop-port to the through-port was greater than 95%, and the drop bandwidth at a full-width at half maximum was 1.5 nm.

This work was partly supported by NEDO within the framework of the "Photonic Network Project," and the IT Program, MEXT.

Photonic Crystal Microwave Resonators for Magnetic Resonance Applications

S. Greulich-Weber, A. von Rhein and E. von Rhein Universitaet Paderborn, Department Physik, Warburger Str. 100, Paderborn, Germany.

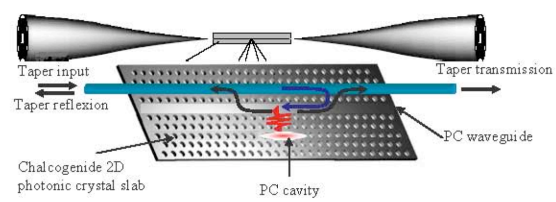
Electron paramagnetic resonance and multiple resonance techniques like electron nuclear double resonance and optically detected magnetic resonance are powerful tools for the investigation of defects in solids. Recently high frequency sources (100 GHz) at reasonable costs became available for magnetic resonance (MR) spectroscopy providing higher spectral resolution and in principle higher sensitivity compared to lower frequencies. Usually the microwave absorption due to the MR signal is measured using a microwave bridge balanced by a microwave resonator containing the sample. At high frequencies the resonator becomes rather small which requires the development of new resonator designs. Especially for optical detection of MR optical access to the sample is needed which at high frequencies only allows the use of Fabry-Perot resonators, which provide relatively small quality factors. We show new resonator designs on the basis of photonic crystals also suitable for low frequency MR providing additional features not known from conventional resonators. These resonators are realized by defects in two-dimensional photonic crystals, in which the magnetic mode of the irradiated micowave needed for MR measurements is localized. These structures yield resonances with unusual high Q-factors. We present calculations on this kind of resonators as well as experimental results. Photonic crystal microwave resonators have numerous advantages compared to conventional resonators for MR, especially at high frequencies and for optically detected MR, such as easy application of additional modulation or high frequency fields and optical access to samples in the resonator.

Chalcogenide photonic crystal microdevices—Towards effective all-optical switch

C. Grillet, D. J. Moss, D. Freeman, S. Madden, B. Luther-Davies and B. J. Eggleton,
CUDOS, University of Sydney, New South Wales 2006, Australia

We present a novel platform for next generation of compact all-optical switch [1]. The fundamental innovation of our approach involves the use of chalcogenide glass [2] as a host material for two dimensional planar photonic crystal devices. These two-dimensional nonlinear chalcogenide planar photonic crystals provide a flexible and powerful approach for controlling light in microscale photonic circuit.

The configuration investigated consists of a photonic crystal waveguide (line defect in the lattice) coupled to a cavity defect, and designed for optimal optical bistability. The optical characterization is performed using the fiber taper evanescent coupling technique [3], adapted to two-dimensional chalcogenide planar photonic crystal devices.



Schematic of the coupling scheme between the fiber taper and the PC waveguide/side-coupled cavity system.

The configuration investigated consists of a photonic crystal waveguide (line defect in the lattice) coupled to a cavity defect, and designed for optimal optical bistability. The optical characterization is performed using the fiber taper evanescent coupling technique [3], adapted to two-dimensional chalcogenide planar photonic crystal devices.

[1] M. Soljaćiş, et al, *Phys. Rev. E*, **66**, 055601 (2002)
[2] D. Freeman, et al, submitted for *PECS-VI*, (2005).
[3] P. E. Barclay, et al, *J. Opt. Soc. Am. B*, **20**, 2274 (2003)

Experimental analysis of true left-handed behavior and transmission properties of composite metamaterials

K. Güven,[1] K. Aydin,[1] and E. Ozbay[1,2]
[1]Department of Physics, Bilkent University, 06800 Ankara, TURKEY
[2]Nanotechnology Research Center, Bilkent University, 06800 Ankara, TURKEY

We report the true-left handed transmission of a composite metamaterial (CMM) consisting of periodically stacked split-ring resonator (SRR) and wire structures. In particular, the negative permeability response is demonstrated by comparing SRR and closed-split resonator structures. We confirm experimentally that the effective plasma frequency (negative permittivity cut-off) of the CMM is lower than the plasma frequency of wires.[1]

We further investigate the effect of intralayer and interlayer disorder to transmission spectrum of CMMs, arising from aperiodic fabrication of SRR layers and misaligned stacking. When the intralayer disorder becomes comparable to the periodicity, the magnetic gap of SRRs and consequently the left-handed transmission band of CMM shrinks and transmission intensity decreases significantly. On the other hand, the SRR transmission spectrum is rather immune to misalignment effects, which is more likely to occur.[2]

[1] K. Aydin, K. Guven, M. Kafesaki, L. Zhang, C. M. Soukoulis, and E. Ozbay, *Optics Letters*, **29**, 2623 (2004).
[2] K. Aydin, K. Guven, N. Katsarakis, C. M. Soukoulis, and E. Ozbay, *Optics Express*, **12**, 5896 (2004)

Topology Optimised Photonic Crystal 1x4 Waveguide Splitter

L.H. Frandsen, A. Harpøth, K.K. Hede, M. Kristensen, P.I. Borel
COM, Technical University of Denmark, Building 345v, 2800 Kgs. Lyngby, Denmark
J.S. Jensen, O. Sigmund
MEK, Technical University of Denmark, Building 404, 2800 Kgs. Lyngby, Denmark

A photonic crystal waveguide (PhCW) 1x4 splitter has been constructed from PhCW 60° bends [1] and Y-splitters [2] that have been designed individually by utilising topology optimisation [3]. The splitter has been fabricated in a silicon-on-insulator material (Fig. 1) and exhibits a broadband splitting for the TE-polarisation with an average excess loss of 1.55±0.54 dB for a 110 nm bandwidth (Fig. 2). The 1x4 splitter demonstrates that individual topology-optimised parts can be used as building blocks to realise high-performance nanophotonic circuits.

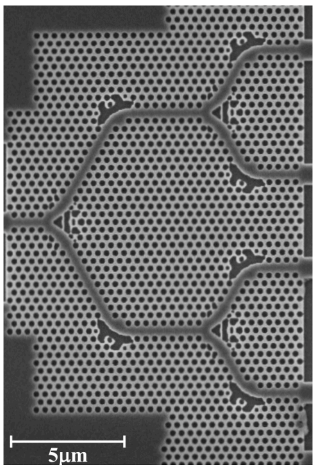


Fig. 1 SEM picture of the splitter.

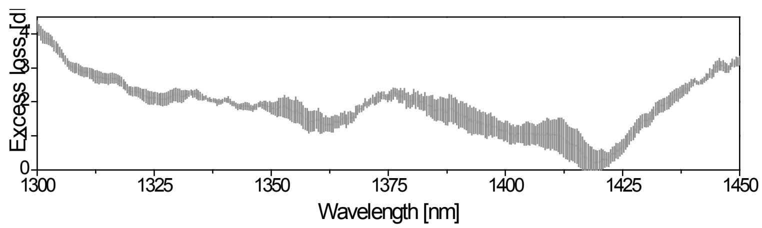


Fig. 2 Normalised transmission spectrum from the 1x4 splitter. The error bars express the variation in the measured transmission from the different output arms.

[1] L.H. Frandsen *et al.*, *Optics Express*, **12**, pp. 5916-5921 (2004).
[2] P.I. Borel *et al.*, to appear in *Electron. Lett.* (2005).
[3] J.S. Jensen and O. Sigmund, *App. Phys. Lett.*, **84**, pp. 2022-2024 (2004).

Optimal design of a micro-scaled de-multiplexer

Andreas Håkansson and José Sánchez-Dehesa
Wave Phenomena Group, Nanophotonic Technology Center,
Polytechnic University of Valencia, C/ Camino de Vera s/n, E-46022, Valencia, Spain.

A method of inverse design [1] that consists of an integration of the Multiple Scattering Theory with a Genetic Algorithm is applied to generate an optical wavelength de-multiplexer, based on Si cylinders placed in a background of SiO2. This ultra compact device, only 2mm thick, is designed to separate the two wavelengths 1.55mm and 1.50mm with a minimal possible cross-talk. The optimization is carried out by removing cylinders from a perfectly crystalline cluster, made of only five layers, and in this way guide the flow of light through the slab by tailoring the scattering process in-between the cylinders. This method has earlier been successfully used to design photonic [1] and phononic [2-3] devices.

[1] L. Sanchis, A. Håkansson, D. Lopez-Zanón, J. Bravo-Abad and J. Sánchez-Dehesa, *Appl. Phys. Lett.,* **84**, 4460 (2004)

[2] A. Håkansson, L. Sanchis, and J. Sánchez-Dehesa, *Phys. Rev. B*, **70**, 214302 (2005)

[3] A. Håkansson, J. Sánchez-Dehesa and F. Cervera, *Appl. Phys. Lett.*, **86**, 054102 (2005)

Theoretical Investigation on Photonic Bandgap of Nesting Complex-period Photonic Crystals

Yu. Han, and Kai. Xie,
Department of Materials Engineering and Appiled chemistry, National University of Defense Technology, Changsha, Hunan, China.

The photonic bandgap of a new 2D nesting complex-period (NCP) structures (Fig 1.) were theoretically investigated. The objective of the Investigation was to find out the difference of the PBG between the new NCP structures and simple-period (SP) structures, and then to ascertain the effect of complex period and the suitable application of them.
Optical responses were calculated for air or PLZT pillars In porous alumina. Fill ratio In calculation ranged between 0.17 to 0.46.Calculation revealed that the PBG of NCP structure was effected by both fill ratio of outside period (R/D) and fill ratio of inside period (r/d). And the contributions of them are different. When R/D of NCP was the same as the fill ratio of SP, because there were Inside periods In NCP structure, the PBG of NCP departed a lot from that of SP, and the width of PBG of NCP was much less than that of SP (Fig 2). In addition, when R/D was fixed, the more r/d was, the longer wavelength of PBG was, which differed from SP.

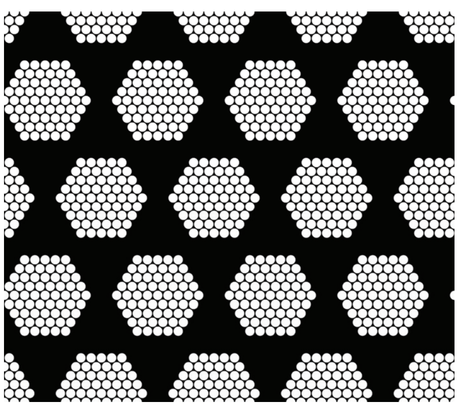


Fig1. new 2D NCP structures. The fill ratio of outside period (R/D) was 0.36, the fill ratio of Inside period (r/d) was 0.46.

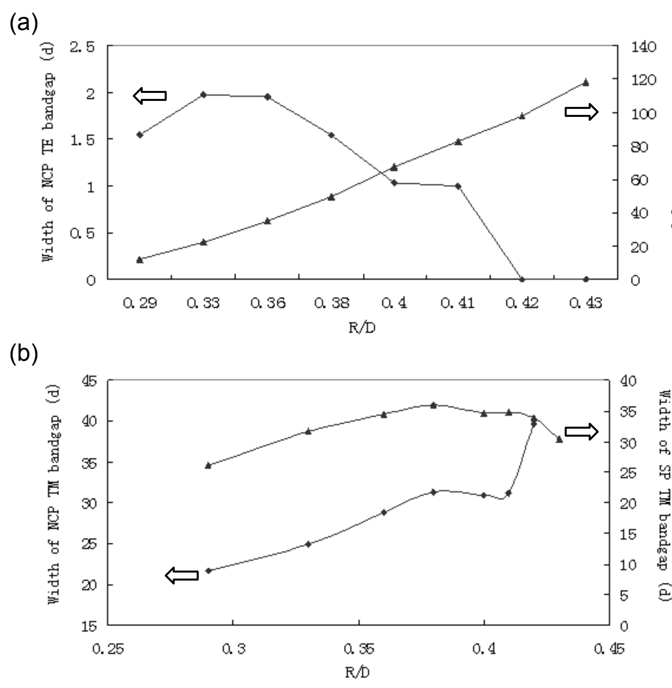


Fig2. Width of bandgap for PLZT/Al_2O_3. (a) TE, (b) TM.

Effect of the dielectric layer on the transmission enhancement for metal hole arrays in terahertz region

F. Miyamaru, M. Tanaka and M. Hangyo
Institute of Laser Engineering, Osaka University, 21st Century Plaza 3F, 2-6 Yamadaoka, Suita, Osaka 565-0871, Japan

For the metal slabs perforated periodically with circular holes, the enhanced band-pass transmission characteristic has been observed. The mechanism of this phenomenon is attributed to the resonant excitation of the surface plasmon-polaritons (SPPs) at the metal-air (or dielectric) boundary. The SPP is not supported on the flat metal surface in the terahertz (THz) region because metals are regarded as a nearly perfect conductor in this region. However, the SPP-like mode is supported on the perforated metal surface according to Pendry et al. [1]. In this paper, we clarified the role of the SPP in the Pendry's sense in the enhanced transmission phenomenon for the metal hole arrays by measuring the effect of the dielectric film attached on the metal surface.

We used polypropylene films, the refractive index of which was 1.7, as the dielectric films and attached them on the output side of the metal surface. The transmission spectra have a characteristic peak which shift to the low frequency side with increasing the film thickness from 0 (no film) to 200 μm as seen in Fig. 1. This result is ascribed to the decrease of the resonant frequency of the SPP excited on the output surface by the attachment of the dielectric film. The peak frequency shift shows a tendency of saturation in the thick region (Inset of the figure). Since the electric field of the SPP attenuates exponentially with going away from the metal surface, this result indicate that the SPP plays the very important role for the enhanced band-pass transmission property of the metal hole array.

[1] J. B. Pendry *et al*., Science **305**, 847 (2004).

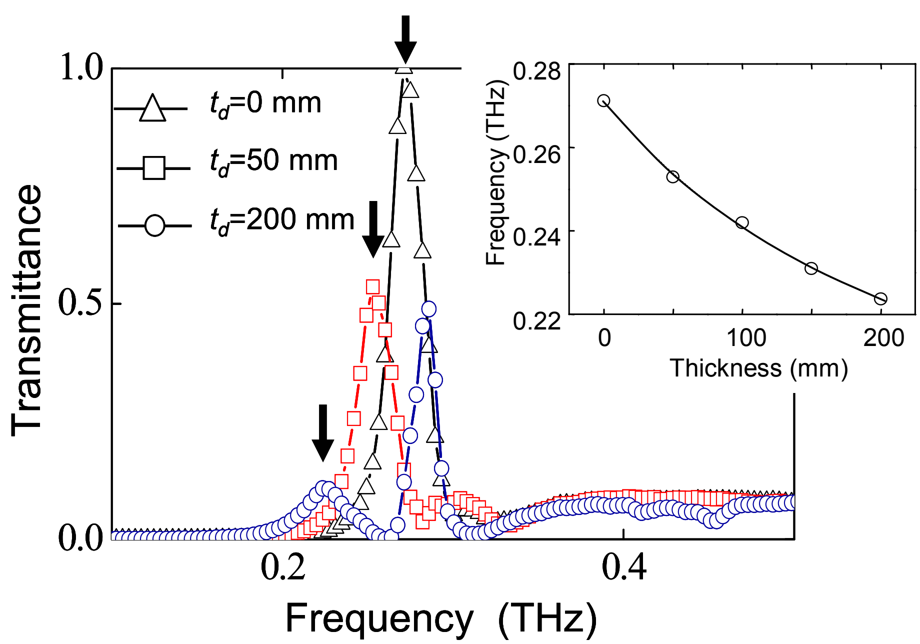
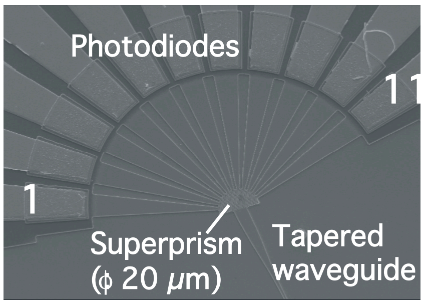


Fig. 1 Measured transmission spectra of the metal hole arrays for various film thicknesses. Inset shows the peak frequency as a function of the film thickness attached on the metal surface.

Photodiode Integrated Superprism Demultiplexer Based on GaInAsP/InP

H. Heidrich, S. Golka, K. Janiak, J.-R. van Look,
U. Troppenz, C.M. Weinert, H.J. Ehrke, R. Stenzel
Fraunhofer Institute for Telecommunications, Heinrich-Hertz Institut,
Einsteinufer 37, D-10587 Berlin, Germany

One of the key functions in WDM (Wavelength Division Multiplexing) systems is wavelength monitoring. We fabricated and analyzed a compact superprism based wavelength monitor for e.g. Coarse WDM (CWDM) channel allocations in the 1.5 µm spectral window. The superprism arrangement is according to [1]. Integrated photodiodes result in a small footprint and simple packaging as only a single waveguide interface is required. A photonic crystal triangular lattice pattern was formed (CAIBE etched [2]) within a semicircular area forming the demultiplexer (cf. figure) as in [1]. For the realised device the superprism effect is observed for 1.4…1.6 µm.



[1] L. Wu, M. Mazilu, T. Karle, and T.F. Krauss, IEEE J. Quantum Electronics, Vol. 38, No. 7, pp. 915-918, 2002.
[2] S. Golka, K. Janiak, H.-J. Hensel, H. Heidrich, E. Schwoob; H. Benisty, 15th Indium Phosphide and Related Materials Conf. (IPRM), 12.-16.05.2003, San José (USA).

Comparison of Different PhC Waveguide Couplers in InGaAsP/InP

J. van Look, S. Golka, K. Janiak, C.M. Weinert, H. Heidrich
Fraunhofer Institute for Telecommunications, Heinrich-Hertz Institut,
Einsteinufer 37, 10587 Berlin, Germany

For small footprint integrated optics low loss coupling between ridge waveguides and Photonic Crystal (PhC) waveguides is essential. We fabricated and analyzed different PhC coupler geometries (examples in Fig. 1) in a triangular PhC lattice (CAIBE etched [2]). Different coupler layouts such as step type (shown in Fig. 1a), line-gradient type (as proposed by [1]), continuous type and field-gradient type (shown in fig. 1b) were compared in measurement and calculation. We measured the transmission around 1.5 µm wavelength and found a typical improvement of 3 dB per tapered interface compared to reference structures without tapers. Best results were achieved at ultra compact taper lengths < 5 µm. Good agreement between the end-fire measurements and the 2D finite element simulations could be observed.

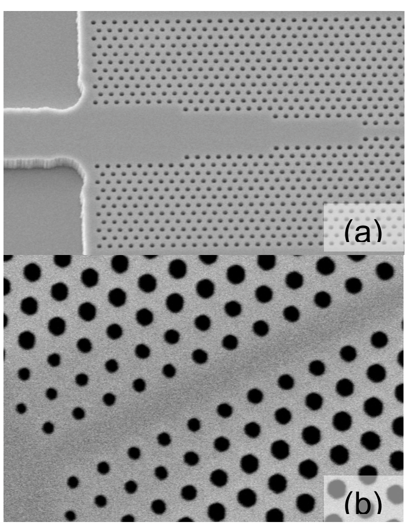


Fig. 1: SEM photograph of fabricated PhC Couplers

[1] A. Talneau, P. Lalanne, M. Agio, C.M. Soukoulis, Optics Lett., Vol. 27, No.17, pp. 1522, 2002.
[2] S. Golka, K. Janiak, H.-J. Hensel, H. Heidrich, E. Schwoob, H. Benisty, 15th Indium Phosphide and Related Materials Conf. (IPRM), 12.-16.05.2003, San José (USA).

Deterministic coupling of photonic crystal nanocavity modes to single quantum dot excitons

K. Hennessy, A. Badolato, P. M. Petroff, E. L. Hu
Departments of Electrical & Computer Engineering and Materials, University of California, Santa Barbara, CA 93106

M. Atatüre, J. Dreiser A. Imamoğlu
Institute of Quantum Electronics, ETH Hönggerberg HPT G12, CH-8093 Zurich, Switzerland

We demonstrate a deterministic approach to realize devices for cavity quantum electrodynamics based on precise spatial and spectral coupling between a single InAs quantum dot (QD) and a GaAs photonic crystal (PC) nanocavity.

We position the QD in an ultra-small mode volume PC nanocavity, $V < (\lambda/n)^3$, by stacking tracer QDs above the viable QD up to the surface. We then fabricate a nanocavity around the tracer dot, thus locating the QD in the center of the PC membrane. By using a digital etching process, we controllably tune the nanocavity mode in small steps until we have spectrally engaged the QD.

By fine-tuning the high-*Q* cavity modes into resonance with any given exciton state of the QD, we observe high Purcell factors and non-trivial QD multi-exciton dynamics in **all** fabricated structures.

Double Inverse Opals -A New Approach for a Switchable Complete Photonic Bandgap

C. Hermann*, C. Jamois*, A. Klaedtke*, D.P. Aryal*, T. Ruhl°, P. Spahn° and O. Hess*,
*Advanced Technology Institute, School of Electronics & Physical Sciences, University of Surrey, Guildford, United Kingdom °German Polymer Institute, Technical University of Darmstadt, Darmstadt, Germany

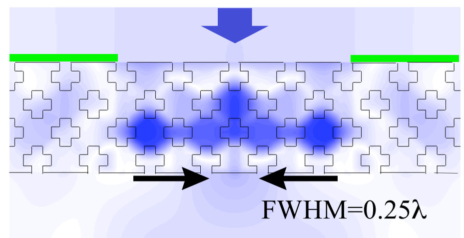
The intriguing optical properties of photonic crystals have stimulated many design and application concepts over the past nearly two decades. As technology advances there is now not only a desire for static systems with certain properties but also an increasing interest in tunable or switchable structures.

In this work we present a novel approach to achieve a switchable complete photonic bandgap. We show that a structure consisting of a high index inverse opal backbone with additional movable dielectric scatterers with a lower refractive index in the air voids has a complete photonic bandgap for certain positions of the scatterers while it is closed for other positions. This is mainly due to a shift of frequencies at the air band where the eigenmodes are most sensitive to changes of the refractive index in low-index regions. We perform a numerical analysis of the parameter dependencies of this effect and discuss prospects of an experimental realisation, including a proposal for the switching process itself by incorporating metallic particles into the movable scatterers and the application of external fields.

Superfocusing of light beams below the diffraction limit by photonic crystals with negative refraction

A. Husakou, J. Herrmann
Max Born Institute, Max Born Str. 2a, D-12489, Berlin, Germany

Usual optical elements cannot focus a light beam to a spot with a diameter smaller than half of the wavelength of the light. Recent work has shown that photonic crystals below the bandgap can exhibit negative refraction and amplify evanescent components. In contrast to previously studied imaging, in the case of focusing of a beam no seed evanescent waves are present in the input beam. Therefore we introduce directly before the slab of the photonic crystal an aperture or a saturable absorber which creates from the input beam weak evanescent components of sufficient amplitude. By numerical solution of the Maxwell equations we demonstrate the amplification of evanescent components with a constructive superposition and focusing to a spot below the diffraction limit for a realistic photonic crystal. In the Figure, superfocusing to a spot with FWHM of 0.25λ. is shown for a 2D lattice of holes in GaAs with a lattice constant of 0.191λ, and an aperture width of 1.15λ.



Efficient calculation of the quality factor of photonic crystal cavity

Ming Li, J. R. Cao, Z. Y. Li, M. Miyawaki, and K. M. Ho
Department of Physics, Ames Laboratory, Iowa State University, Ames, IA 50011 USA and Canon Development Americas Inc., Irvine, CA 92618 USA and Institute of Physics, Chinese Academy of Sciences, P. O. Box 603, Beijing 100080, China

The transfer matrix method (TMM) is used to study the transmission coefficient of optical cavities embedded in a photonic crystal slab. This is an efficient method to obtain the cavity quality factor and the peak transmission frequency for a large number of cavity geometries. The results show that the quality factor can exceed 10,000 with a slab of 25 layers with the cavity located at the center layer. There is also a shift for the peak transmission frequency which approaches a fixed value when the number of layers on both side of the cavity is increased.

Fabrication of metallic and ceramic photonic crystals using microtransfer molding methods

J. H. Lee, H. Kang, C. H. Kim, J. H. Ahn, W. Y. Leung, Y. S. Kim, R. Biswas, C. H. Oh, K. M. Ho, and K. Constant
Department of Physics, Ames Laboratory, Iowa State University, Ames, IA 50011, USA and Hanyang University, Korea

We present fabrication methods and optical data of 3D metallic and dielectric photonic crystals. The fabrication methods are based on soft lithographic techniques that include layer-by-layer template fabrication, structure alignment and ceramic infiltration. These methods can be easily extendable for introduction of defects in 3D photonic crystals. With these techniques, freestanding metallic crystals and titania crystals on a silicon substrate have been fabricated. Since the crystals have systematical spatial deviations in their structures, structure-dependent optical properties were investigated in a single sample by means of an infrared spectral imaging. We will present the effect of alignment errors on the optical signature in the 3D photonic crystals fabricated by these methods. The tolerance of alignment for both metallic and dielectric 3D photonic crystals will also be discussed.

Quasi-three-dimensional photonic crystal defect microcavity

Y. -L. D. Ho, T. Cao, P. S. Ivanov, M. J. Cryan, I. J. Craddock, C. J. Railton, and J. G. Rarity

Centre for Communications Research, Department of Electronic and Electrical Engineering, University of Bristol, Bristol, BS8 1UB, UK.

We use the 3-D finite difference time domain (FDTD) method to analyze micro-pillar microcavities based on distributed Bragg reflectors (DBR) and more sophisticated structures consisting of quasi-3D photonic crystal defects. The aim is to produce low modal volume high Q cavities. The micro-pillar microcavity is modelled on III-V semiconductor materials (AlAs/GaAs) with quarter wavelength period stacks resonant at 994 nm wavelength. For small diameter pillars the quality factor Q of the cavity is reduced by light scattering from the sidewalls. Hence we look at microcavities including lateral 2D photonic crystals to suppress sidewall leakage. We input a few-cycle excitation pulse at the cavity centre then monitor the cavity ringdown using a probe above the pillar. From this we obtain the resonant frequencies and estimates of Q-factors ($Q=\lambda/\Delta\lambda$). The effective cavity volume V_{eff} can also be estimated. We calculate improved Q/V_{eff} values for photonic crystal defect microcavities.

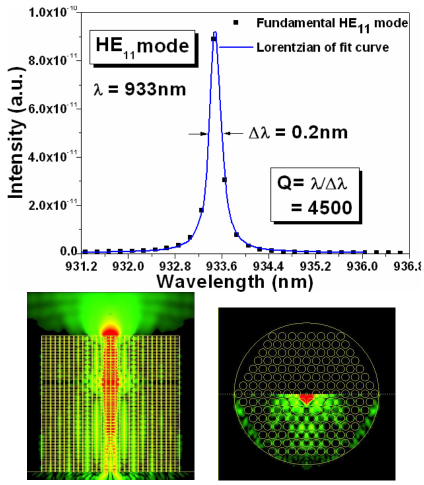
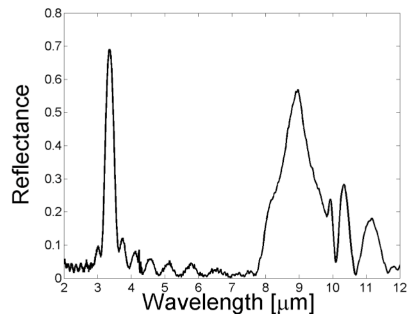


Fig. 1: Resonance and E-field in a photonic crystal microcavity.

A three-dimensional photonic crystal with a polaritonic gap

Herman Högström and Carl G. Ribbing*
Department of Engineering Sciences, The Ångström Laboratory, Uppsala University
Box 534, SE-751 21 Uppsala, e-mail: herman.hogstrom@angstrom.uu.se
*and Dept. of Functional Materials, Swedish Defense Research Agency, Linköping, SWEDEN

In photonic structures gaps have different origins. Oscillators e.g. electrons or ions, give rise to imaginary k-vectors for photons in various wavelength intervals. Another way to obtain an imaginary k-vector is to structure a material periodically, i.e. a photonic crystal. Photonic crystals consisting of dielectric or metallic materials have been successfully fabricated in one to three dimensions, but not much has been done using polaritonic materials. We demonstrate, to our knowledge for the first time, an experimental demonstration of a three dimensional photonic crystal with a polaritonic gap, PG. The crystal was made by sedimentation of silica microspheres with d=1.58μm that formed a fcc structure. Bulk silica has a reflectance band close to λ=9 μm. The reflectance peak originating from the fcc structure results in a peak at 3.4 μm. Both peaks are clearly seen in the reflectance spectrum. Since the PG is a bulk material property it is not obvious that small structures, e.g. microspheres, will exhibit bulk optical properties. This contribution demonstrates the possibility to simultaneously have a polaritonic and a structural gap in a three-dimensional photonic crystal.



Reflectance spectrum for a three dimensional photonic crystal made of silica spheres with d=1.58 μm.

Precursor of isotropic photonicgap obtained in circular photonic crystal

N. Horiuchi, Y. Segawa, T. Nozokido [a], K. Mizuno [a], and H. Miyazaki [a]
Photodynamics Research Center, RIKEN, 519-1399, Aoba, Aramaki, Sendai, 980-0485, Japan
horiuchi@riken.jp, Tohoku Univ.[a]

The isotropic photonic gaps (PG) can be obtained in a circular photonic crystal (CPC) which is composed of alumina rods[1]. For the non-periodic lattice array system, a short-range order seems to contribute the formation of PG, because the position of the PG depends on the minimum distance between the rods in CPC. In this study, the relative wave intensity $|E|^2$ between two dielectric rods is measured to investigate the origin of the isotropic PG. A millimeter wave was irradiated to a pair of parallel alumina rods (radius r = 3mm, distance d = 9 mm, refractive index n =3.1) in the direction θ from the alignment line. Even though θ is as large as 30°, the precursor of the PG was observed in the spectrum. Considering each mode profile inside the dielectric rods at the frequencies (9 and 14 GHz), it turns out that the formation of the PG is associated with Mie resonance between two dielectric rods.

[1] Horiuchi et al., Opt. Lett. **29**, 1084 (2004).

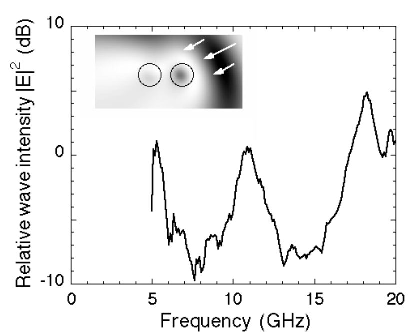


Fig. Relative wave intensity spectrum obtained at the center of the two rods (θ = 30°). Inset is the calculated intensity distribution around the rods.

Observation of photonic bands of 1D photonic crystals by irradiating an evanescent wave from a high-energy electron beam

N.Horiuchi, Y.Segawa, Y.Shibata[a], K.Ishi[a], T.Tsutaya[a], Y.Kondo[a], M.Kanbe[a], H.Miyazaki[a], F.Hinode[a], S.Yamaguchi[b], T.Ochiai[c] and K.Ohtaka[b]
Photodynamics Research Center, RIKEN, 519-1399, Aoba, Aramaki, Sendai, 980-0485, Japan horiuchi@riken.jp, Tohoku Univ.[a], Chiba Univ.[b], NIMS[c]

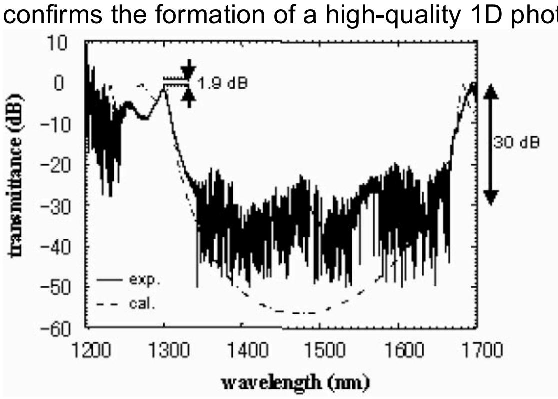
Smith-Purcell radiation (SPR) was observed from a two-dimensional photonic crystal (PC)[1]. However, peculiar light emission was also observed. The slope of the dispersion relations between energy and wavenumber was smaller than the light line. In this study, we investigate the mechanism of the peculiar light emission from a PC. To simplify the analysis, one-dimensional PCs were fabricated by cylinders of teflon (dielectric constant: ε = 2.05), fused quartz (ε = 4.41) and aluminum. The dispersion lines of SPR and the peculiar light emission were observed from the PCs of teflon and fused quartz, while only the lines of SPR were observed from that of aluminum. The photonic band was calculated by the Korringa-Kohn-Rostoker formalism on the basis of vector cylindrical harmonics. The calculated curves showed good agreement with those of the experimental results. From these facts, it is inferred that the peculiar light emission is related with the photonic band.

[1] K. Yamamoto et al., *Phys. Rev. E* **69**, 045601 (2004)

Transmission characteristics of one-dimensional photonic crystals fabricated using high-aspect-ratio Si etching

Kazuhiko Hosomi[1,2,3], Toshihiko Fukamachi[1,2,3], Hiroji Yamada[1], Toshio Katsuyama[1,2] and Yasuhiko Arakawa[1] NCRC, Univ. of Tokyo[1], OITDA[2], Central Research Laboratory, Hitachi, Ltd.[3] 4-6-1, Komaba, Meguro-ku, Tokyo 153-8505, Japan

Using high-aspect-ratio Si etching, we made 1D photonic crystals consisting of silicon plates 300 nm thick and 10 μm deep. The high-aspect-ratio Si etching was achieved with cryogenic etching, in which the Si substrate was cooled to cryogenic temperature with liquid nitrogen. The measured transmission spectrum and the theoretically predicted spectra are shown in the figure. This figure shows that there was an obvious band gap (transmittance suppressed by greater than 30 dB) and a small transmission loss. The dash-dot-dash line in the figure shows the theoretically predicted spectrum calculated using the characteristic matrix method. The measured transmission spectrum is well reproduced by spectrum calculated for a 1D photonic crystal. This agreement confirms the formation of a high-quality 1D photonic crystal.

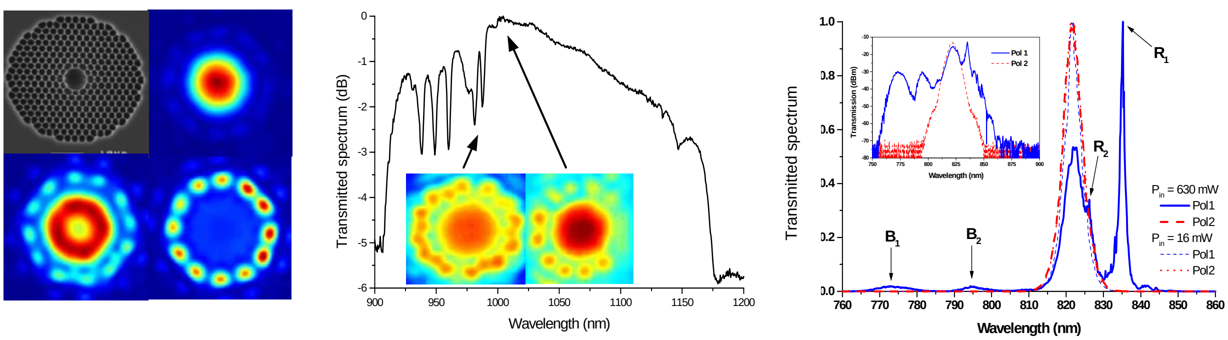


A part of this work was performed under management of OITDA supported by NEDO and IT Program supported by MEXT

Linear and nonlinear effects due to interface modes in hollow-core photonic crystal fibers

G. Humbert, F. Benabid, J. C. Knight and P. St. J. Russell,
Photonics and Photonic Materials Group, Department of Physics, University of Bath,
Claverton Down, Bath, BA2 7AY, United Kingdom

In terms of attenuation, hollow-core photonic crystal fiber (HC-PCF) represents the most advanced of photonic bandgap structures, exhibiting guidance lengths of the order of kilometres. Light is trapped in the core by the photonic bandgap of the cladding, which enables the propagation of light in unusual modes and makes these fibers a rich platform for studying various linear and nonlinear optical effects.
In specific wavelength ranges, interface or "surface" modes are confined to the core surrounds by the bandgap cladding. These modes interact with the core modes and strongly affect their properties, such as attenuation, overlap with the glass and dispersion. Here, we describe observations of linear and nonlinear interactions between interface and core modes of HC-PCFs.



(a) (b) (c)

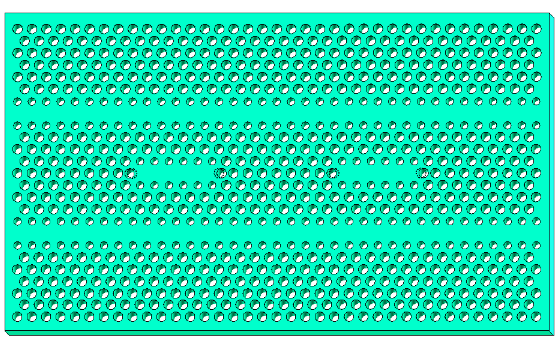
(a) SEM and output near field Images of core modes and interface modes of a HC-PCF, (b) transmitted spectrum and spectrally selected output near field images of a white light source passed through 5 m length of HC-PCF, (c) transmitted spectrum of surface modes excited by fs laser pulses with different average power and input polarizations.

Design of an extremely high-Q in-plane-type photonic-crystal channel-drop filter for the DWDM applications

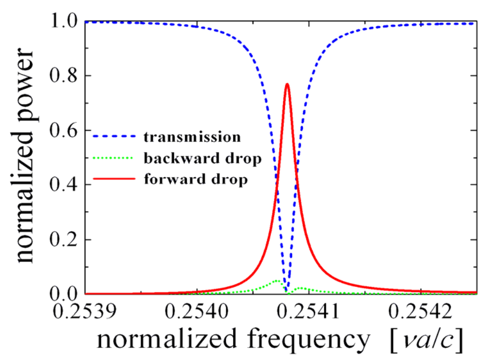
Kyu H. Hwang, G. Hugh Song, and Chanmook Lim,
Department of Information and Communications,
Gwangju Institute of Science and Technology, Gwangju 500-712, South Korea.
Tel: +82-62-970-2210, 2298, E-mail: khhwang@gist.ac.kr, hughsong@gist.ac.kr

In-plane-type channel-drop filters have been designed or demonstrated based on the two-dimensional (2D) photonic-crystal (PhC) [1, 2] and the 2D PhC slab [3-5] structures.

In this presentation, we show that the design of the in-plane-type channel-drop filter based on the 2D PhC slab structure from the modification of the previous design [5] by three-dimensional finite-difference time-domain (FDTD) simulation has been greatly improved. The Q factor of the filter has been calculated around to be 13,300 and the forward-drop power spectrum has been obtained to be almost symmetric Lorentzian, which would be fairly adequate for dense wavelength division multiplexing (DWDM) applications. Over than 77 % of the incident power at the input port has been transferred to the forward-drop port, and the transmitted and the backward-drop powers have been reduced below –18 dB and –22 dB, respectively, at the center frequency. We have shown that the improved design of the extremely high-Q in-plane-type channel-drop filter based on the 2D PhC slab structure has the possibility of the realization as a DWDM add-drop multiplexer when the nano-photonic integrated-circuit fabrication technology is fully developed.



(a)



(b)

Fig. 1. (a) Schematic of an in-plane-type channel-drop filter based on the 2D PhC slab structure. (b) Frequency responses of the designed channel-drop filter.

[1] S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and H. A. Haus, *Phys. Rev. Lett.* **80**, 960-963 (1998).
[2] K. H. Hwang, S. Kim, and G. H. Song, *SPIE* **5360**, 405-410, (2004).
[3] H. Takano, Y. Akahane, T. Asano, and S. Noda, *PECS-V*, 152, (2004).
[4] K. H. Hwang and G. H. Song, *ECOC* **5**, 76-77, (2004).
[5] K. H. Hwang, C. Lim, J. W. Lee, K.-B. Chung, and G. H. Song, submitted to *CLEO/QELS* 2005.

Second Harmonic Generation in Highly Nonlinear LiNbO3 Photonic Crystals

Shin-Ichiro Inoue [1, 2,] *

[1] Nanoscience Research Program, RIKEN,
2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan
* Tel & Fax : +81-45-924-5866, E-mail: inoue@riken.jp

Yoshinobu Aoyagi [2, 1]

[2] Department of Information Processing, Tokyo Institute of Technology,
4259 Nagatsuta, Midori-ku, Yokohama 226-8502, Japan

Fabrication and second harmonic generation (SHG) characteristics of two-dimensional (2D) photonic crystal (PhC) waveguides using highly nonlinear LiNbO3 have been demonstrated and studied. Large enhancement of the SHG in ultraviolet (UV) and deep-UV (DUV) regions has been observed in the LiNbO3 PhC waveguide.

We have revealed the physical mechanism of the enhancements of SHG originating from band dispersion nature by comparing the observed nonlinear optical responses with the photonic band structure features examined by 3D finite-difference time- domain calculations and polarized-angular-dependent reflectivity measurements [1-3].

[1] S. Inoue, et al., *Physical Review Letters*, (2005) in press.
[2] S. Inoue, et al., *Physical Review B*, **69**, 205109 (2004).
[3] S. Inoue, et al., *Applied Physics Lett*ers **82**, 2966 (2003).

Origin of Photovoltaic Effect in Metallic Photonic Crystal Slabs

T. Ishihara [AB], A. Christ [C], A.S.Vengurlekar [B], X. Luo [B], C. Kamaga [B], M. Iwanaga [A],
N.A. Gippius [BD], and S.G. Tikhodeev [D],

[A] Department of Physics, Tohoku University, Sendai, Japan
[B] Frontier Research System, RIKEN, Wako, Japan
[C] The Japan Society for Promotion of Science, Tokyo, Japan
[D] General Physics Institute, Moscow, Russia

We report photo-induced voltage across metallic photonic crystal slabs. The effect is ascribed to the photo-rectification effect based on the second-order electromagnetic terms in the equation of motion for carriers. One-dimensional line-and-space resist patterns (1x1 mm^2, typical period of 850 nm) are located on Au or Cr semi-transparent thin film strip. The electric field distribution in the metal is much simpler compared to our previous experiments on engraved metallic gratings, which allows us to make quantitative comparison between the experiment and theory. A collimated P-polarized tunable laser beam (wavelength 800-1000 nm, pulse width 7 ns, typical pulse energy 10 µJ) is incident on the pattern at various angles. Polarization is perpendicular to the grating grooves. The amplitude (typically mV) and sign of the voltage is sensitively dependent on the wavelength and incident angle. With the scattering matrix calculation we analyze the electromagnetic field distribution in the metal, from which the photo-induced voltage is estimated. Finally similar measurements on the prism-coupled metallic thin film system will be compared to those on metallic photonic crystals.

Efficient computational technique for resonances in photonic crystal slabs

N. A. Gippius[a,b], S.G. Tikhodeev[a,b] and T. Ishihara[a)]

[a)] EEL-FRS RIKEN, 2-1Hirosawa, Wako, Saitama,351-0198, Japan

[b)] General Physics Institute, RAS, Moscow, Russia

We report an efficient method for calculation of the resonant modes in photonic crystal slabs (PCS). The energy and quality factor dispersions, near field patterns of the resonances are calculated for different PCS structures. This method improves significantly the mode search procedure based on the scattering matrix formalism [1]. The method is compared with the finite difference in time domain calculations where available. The implementation of the method to describe the resonant features in PCS spectra is discussed. The examples of its application in linear [2,3] and nonlinear photonics [4] modeling are presented.

[1] S. G. Tikhodeev, A. L. Yablonskii, E. A. Muljarov, N. A. Gippius, and T. Ishihara, *Phys. Rev. B*, **66**, 045102 (2002).
[2] A. Christ, S. G. Tikhodeev, N. A. Gippius, J. Kuhl, and H. Giessen, *Phys. Rev. Lett.*, **91**, 183901 (2003).
[3] A. Christ, T. Zentgraf, J. Kuhl ans S. G. Tikhodeev, N. A. Gippius, and H. Giessen, *Phys. Rev. B*, *70*, 125113 (2004).
[4] N.A. Gippius, S.G. Tikhodeev, V.D. Kulakovskii, D.N. Krizhanovskii, A.I. Tartakovskii, *Europhys. Lett.,* **67**, 997 (2004).

Fabrication of MEMS-integrated photonic crystal waveguide and demonstration of its switching operation

S. Iwamoto[1,2], M. Tokushima[3], A.Gomyo[3], H. Yamada[3], S. Ishida[1], H.Higo[2], H. Toshiyoshi[2], and Y. Arakawa[1,2]

[1] RCAST, [2] IIS, University of Tokyo, 4-6-1, Komaba, Meguro-ku, Tokyo, Japan
[3] Fundamental and Environmental Res. Labs., NEC Corp.,
34 Miyukigaoka, Tsukuba, Japan

We report on the successful fabrication of MEMS-integrated photonic crystal (PhC) waveguide device and the first experimental demonstration of mechanically- controlled switching operation. In MEMS-Integarated PhC devices[1], optical characteristics of PhC can be controlled by changing the evanescent interaction between the lightwave in the PhC and an external dielectric structure, which is actuated by MEMS. The device fabricated in this study consists of SOI PhC line-defect waveguide and a 1-μm-thick poly-silicon plate separated by 500 nm from the PhC waveguide. The plate length along the PhC waveguide was 5 μm. By applying a voltage, the plate approaches to the PhC waveguide and the transmitted light through the waveguide can be switched off. We observed the transmittance at a wavelength of 1.55 μm as a function of applied voltage and demonstrated the switching operation with an extinction ration of ~10 dB at an applied voltage of 20V. This scheme can be applied to tune device characteristics of several kinds of PhC devices.

[1] S. Iwamoto and Y. Arakawa, *IEICE Trans. Electron.*, **E87-C**, 351 (2004).

Evaluation of Large-size 2D Photonic Crystal Slabs for Visible Light: as Precursor of 3D Photonic Crystals

M. Iwanaga[A] and T. Ishihara[A,B]
[A]Department of Physics, Tohoku University, Sendai 980-8578, Japan,
[B]Frontier Research System, RIKEN, Wako 351-0198, Japan.

Visible-light-region three-dimensional (3D) photonic crystals (PhC) of large size, typically 1x1x1 mm^3, are targets in our study to fully clarify the novel optical properties and responses. We are fabricating at present two-dimensional (2D) PhC slabs of large size 5x5 mm^2 as precursor materials of the 3D-PhC. To fabricate the large 2D-PhC slabs and 3D-PhC, femtoseconds-laser fabrication and interferential-wave photolithography are utilized to avoid the restriction related to the electron-beam lithography. In the presentation, we will evaluate the large-size structure of submicron-meter period, e.g. 2D-PhC slabs made of photo-polymerized resin and metal-tip arrayed 2D-PhC slabs, by atomic force microscopy. In addition, we will report the basic optical characteristics in detail. Furthermore, the electromagnetic response of the samples will be analyzed by numerical methods: scattering-matrix and finite-difference time domain techniques. The road to large-size 3D-PhC will be also discussed on the basis of the fabrication of the precursor materials.

Dispersion Compensators based on SOI Photonic Crystals

C. Jamois[1], A. Milenin[2], C. Hermann[1], T. Geppert[2], R.B. Wehrspohn[3], and O. Hess[1]
[1]Advanced Technology Institute, University of Surrey, Guildford, Surrey GU2 7XH, UK
[2]Max Planck Institute of Microstructure Physics, Weinberg 2, 06120 Halle, Germany
[3]University Paderborn, Dep. Physics, Warburgerstr. 100, 33098 Paderborn, Germany

Dispersion compensators (DCs) are inevitable for long-range optical data transmission systems. Currently used DC systems with lengths of a few km or m such as dispersion compensating fibers or Fiber Bragg Gratings, respectively, are rather bulky devices. We designed a planar photonic crystal waveguide (PPC WG) with a bandstructure yielding a negative and almost linear dispersion of about 30 ps/nm/mm at 1.55 µm wavelength over a 40 GHz single-channel. This kind of device can be completely integrated into a planar optical circuit. Moreover, tuning of the material properties for fine adjustment after fabrication is possible. The design of this device is based on a W1 waveguide in a hexagonal array of air pores in the SiO2/Si/SiO2 material system. The study of both the bulk PPC and the WG properties required extensive simulations, combining the results by a plane-wave method and by a FDTD code. To improve the relatively poor coupling of light between incoming and outgoing ridge WGs and the PPC WG, we also developed a new taper concept, the W1.5 WG taper. Experimental realization was achieved using standard dry etching equipments by developing RIE/ICP etch processes using a Cr hard mask. With this approach PPC waveguides in pore arrays with pore diameters ~300 nm and depth ~ 1.5 µm have successfully been fabricated.

Experimental demonstration of photonic crystal 4-channel drop filter

Young-Geun Roh[a], Sungjoon Yoon[a], Heonsu Jeon[a], Sangin Kim[b], Hanjo Lim[b]
[a]School of Physics, Seoul National University, Seoul 151-747, Korea
[b]School of Electrical and Computer Engineering, Ajou University, Suwon 443-749, Korea

We report an experimental demonstration of a photonic crystal-based in-plane 4-channel drop filter. By modifying our previous two-dimensional photonic crystal system operating in the microwave region [1], we constructed highly selective and efficient drop filters based on resonant tunneling. By placing designed cavity defects near a bus waveguide, we obtained cavity Q-factor as large as ~500 and higher than 20 dB drop selectivity between ports, all at controlled frequencies. These results are agreed well with FDTD calculation results. In addition, performance improvement due to the reflection feedback from terminated bus waveguide was considered [2].

[1] Y.-G. Roh, *et al.*, *Appl. Phys. Lett.,* **83,** 231 (2003).
[2] S. Kim, *et al.*, *Opt. Express,* **12**, 5518 (2004).

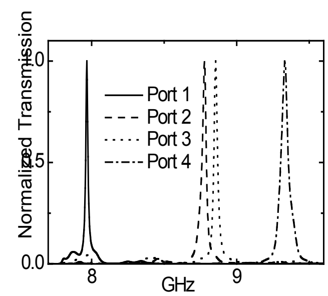


Fig. 0 Transmission spectra for 4 drop channels

Improved performance of nanolaser by chemical surface treatment

Chi-O Cho[a], Heonsu Jeon[a], Jang-Seok Ma[b]
[a]School of Physics, Seoul National University, Seoul 151-747, Korea
[b]Samsung Advanced Institute of Technology, Suwon 440-600, Korea

Single defect photonic crystal nanolaser operating in the 1.55 μm wavelength range was chemically treated to passivate the device surface which is otherwise full of dangling bonds and non-radiative recombination centers. The air-bridge type nanolaser containing multiple InGaAsP quantum wells was reacted with an amine-terminated silane and subsequently with highly charged, high molecular-weight chemicals. The chemical treatment resulted in the redshift of optically pumped laser wavelength by ~10 nm and, more importantly, two-fold increase in laser output and 25% reduction in laser threshold pump power. While the lasing wavelength redshift is simply due to the effective narrowing of etch holes diameter for a given lattice constant, the power enhancement and threshold reduction are attributed to the successful inhibition of non-radiative recombination channels.

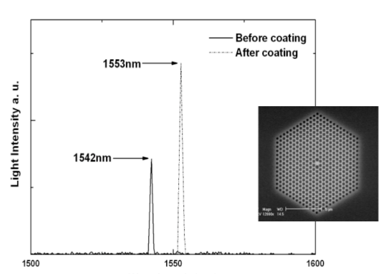


Fig. 1 SEM image of nanolaser and its emission spectra before and after chemical treatment.

Different gaps and bands in Thue-Morse photonic quasi-crystals

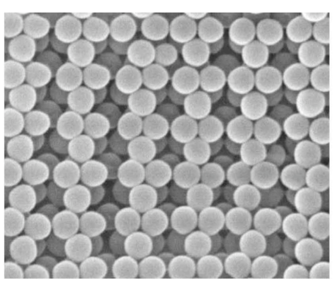
Xunya Jiang[1,2], K.C. Huang[2], Huaping Lei[1] and J. D. Joannopoulos[2] [1]State Key Laboratory of Functional Materials for Informatics, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, 865 Changning Road, 200050, Shanghai, China [2]Department of Physics, Massachusetts Institute of Technology Cambridge, Massachusetts 02139 USA

Photonic band-gap (PBG) can occur not only in the periodic systems, but also in the systems with other spatial correlations. In 1D Thue-Morse dielectric structures, we find two kinds of PBG, traditional gap and fractal gap, which behave quite different in the spectra. And we reveal the physical reason for the gaps, two kinds of the spatial correlation in the Thue-Morse structure. We also studied the localization properties of the eigen-states near these gaps, the states traditional gaps are more like common Bloch states while the states near the fractal gaps have the quasi-localized form. The states can be used in the design of novel optical/photonic cavities.

Fabrication and simulation of individual site defects in opals

F. Jonsson[1], C.M. Sotomayor Torres[1], and J. Seekamp[2],
[1]Tyndall National Institute, University College Cork, Lee Maltings, Cork, Ireland
[2]International University of Bremen, D28758 Bremen, Germany

One major challenge in controlling spontaneous emission in selfassembled photonic crystals is the artificial introduction of defects and cavities. We report on electron beam lithography for the fabrication of individual site defects and lattices in selfassembled threedimensional photonic crystals, fabricated of poly(methyl methacrylate) beads of 500 nm diameter. In the optimization of electron beam parameters for fabrication of defects we employed a fully threedimensional Monte Carlo simulation of the electron scattering. Simulation results obtained so far correspond very well with our experimental results of fabrication [1]. In particular, this work opens the road for inverted opals with light emitting centra placed in targeted individual site cavities.



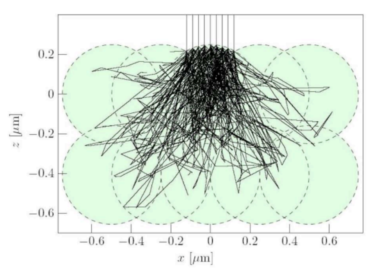


Figure 1. Lattice of defects inscribed in selfassembled PMMA opal (left), and simulated electron scattering from 9×9 grid of injection sites at *E*acc=5.0 kV (right).

[1] F. Jonsson et al., *Microelectron.Eng.*(2005, article in press).

Surface plasmon polaritons in 2D metal nanoparticle structures

S.M. Kachan and A.N. Ponyavina
Institute of Molecular and Atomic Physics, National Academy of Sciences of Belarus,70 Scaryna Ave., Minsk 220072, Belarus

Recent experimental advances in fabrication of ordered and partially ordered planar structures of metal nanoparticles open an avenue for various attractive applications of such “artificial solids”. Their optical properties, determined by the surface plasmon-polariton (SPP) excitations, are quite different from the optical properties of individual nanoparticles and their colloids, since the effects of electrodynamic coupling between the particles become of a great importance.

We study optical properties of a planar monolayer made of noble metal nanoparticles in the framework of the statistical theory of multiple scattering of waves. This approach allows us to analyze the effects of different types and degrees of nanoparticles ordering inside a monolayer over the wide range of particle sizes, concentrations and matrix refractive indices.

The revealed effects include: (i) change of the direction of the *size shift* of SPP’s spectral band, from blue to red with enlarging particles sizes, for highly dense monolayers; (ii) fundamental dependence of both the value and the direction of the *concentration shift* of SPP's spectral band on the size of arranged particles; and (iii) structural modification of the SPP’s spectral band with the change of the degree of particles ordering for particles with sufficiently large diameters. We analyse the obtained results on the basis of the effects of coherent overirradiation for partially correlated particles and additional excitation of higher-order multipoles, under the condition of essentially evanescent effective field reached in close-packed monolayers.

Qualitative behavior of LHM and related meta-materials

Th. Koschny,[1,2] M. Kafesaki,1 R. S. Penciu,[1] N. Katsarakis,[1] E. N. Economou,[1] and C. M. Soukoulis[1,2]
[1]Institute of Electronic Structure and Laser, Foundation of Research and Technology, Hellas (FORTH), P. O. Box 1527, 71110 Heraklion, Crete, Greece
[2]Ames Laboratory and Department of Physics and Astronomy, Iowa State University, Ames, Iowa U.S.A.

We investigate the transmission properties of one-dimensional LHM and related meta-materials of the split-ring resonator (SRR) and continuous wire type, both theoretically and experimentally. Theoretically, we use a fast implementation of the transfer matrix method, which allows us to directly simulate the complex transmission and reflection amplitudes for arbitrary structures inside the unit cell, even for long systems. Moreover, the assumption that the meta-material behaves like an effective medium, we apply an inversion procedure to the obtained scattering data, to retrieve the effective permittivity and permeability as a function of frequency. This allows us to show the negative index of refraction $n(\omega) < 0$ together with simultaneously $\varepsilon_{eff}(\omega) < 0$ and $\mu_{eff}(\omega) < 0$ inside the left-handed bandpass for the one-dimensional materials and normal incidence.

We show that the explanation for the LHM behavior is more complicated than just the combination of the negative $\mu_{eff}(\omega)$ provided by the SRRs with the negative $\mu_{eff}(\omega)$ from the wires, and *we propose a simple analytic model for this behavior*. Our model allows the qualitative interpretation of the complete low frequency spectrum (up to roughly three times the magnetic resonance frequency) of a meta-material. It also explains the occasional appearance of right-handed instead of the expected left-handed bandpasses in LHM around the SRR resonance. The model’s validity is confirmed by a variety of associated experimental measurements, concerning meta-material structures and their various components and variants.

Photonic Crystal Dispersion Compensators

M. Kamp[1], J. Zimmermann[1], B.K. Saravanan[2], S. Anand[3], R. März[2] and A. Forchel[1]

[1]Technische Physik, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany
[2]Infineon Technologies AG, Corporate Research, 81730 Munich, Germany
[3]Royal Institute of Technology, Electrum 229, Kista 16440, Sweden

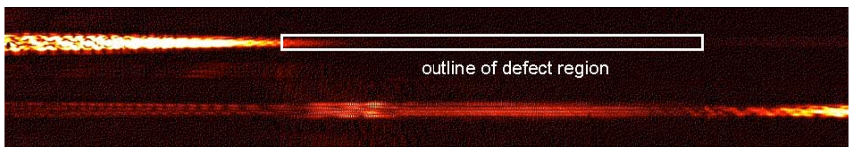
We have realized tunable dispersion compensators based on photonic crystal (PhC) waveguide Fabry-Pérot resonators. The resonators are formed by two PhC sections acting as partial reflectors in a linear defect waveguide. The PhC consists of a triangular lattice of air holes etched into a passive InGaAsP/InP heterostructure with a lattice constant a = 400 nm and an air filling factor of 35 %. Characterization was performed at 1.5 µm wavelength with an external tunable laser source. The transmission of the resonators shows periodic Fabry-Perot resonances with 100 GHz channel spacing and quality factors up to 15,000.

The group delay of the devices was measured using a phase shift technique. The light of the tunable laser source was modulated at 3 GHz using a $LiNbO_3$ Mach-Zehnder modulator. A phase sensitive detection of the transmitted light is used to obtain the phase shift of the modulated signal, which is proportional to the group delay. The derivative of the group delay as a function of the probe wavelength gives the group velocity dispersion. We obtain values ranging from –250 ps/nm to +250 ps/nm at wavelengths around 1.55 µm, sufficing to compensate for the dispersion of 15 km standard single-mode fiber. A temperature variation of only $\Delta T = 7\ ^\circ C$ corresponding to a variation of the effective refractive index of $\Delta n \approx 2\times10^{-3}$ is sufficient to tune the resonator curve over the full free spectral range of 100 GHz.

Slow light, modal dispersion and mini stop bands in photonic crystal waveguides: experiment and modelling

T.J. Karle, T.F. Krauss, W. Bogaerts[#], H.[*] Gersen[†], R.J.P.Engelen , J.P. Korterik[†],
N.F. van Hulst[†], and L. Kuipers[†*]
Ultrafast Photonics Collaboration, University of St Andrews, UK

We have probed the modal dispersion of planar photonic crystal (PhC) waveguides fabricated on SOI. Experimentally, we have imaged the light above the surface of the waveguides using a pulsed laser source with a phase sensitive Near-field Scanning Optical Microscopy (NSOM). This has allowed us to show the real space observation of fast and slow pulses propagating inside a W3 PhC waveguide. Local phase and group velocities of modes are measured. For a specific optical frequency we observe a localized pattern associated with a flat band in the dispersion diagram. Movement of the field is hardly discernable in a 3ps time window: its group velocity would be at most c/1000 [1]. The huge trapping times without the use of a cavity should open new perspectives for dispersion and time control within PhCs.



Pulsed laser excites modes of a PhC waveguide.
The time elapsed between these two frames is 2.8ps

[1] H. Gersen, et al, *Phys. Rev. Lett.*, accepted for publication.

Woodpile-type photonic crystals composed of air columns

T.Katsuyama[1,2], K.Hosomi[1-3], T.Fukamachi[1-3],H.Yamada[1], K.Aoki[1] and Y.Arakawa[1]
[1]NCRC, IIS, University of Tokyo, 4-6-1, Komaba, Meguro-ku, Tokyo 153-8505, Japan,
[2]OITDA, and [3]Hitachi CRL

Three-dimensional photonic crystals are ultimate light-confining structures. However, realizing these structures is difficult due to complicated fabrication techniques. We will describe woodpile-type PhCs composed of air columns, which can be fabricated using a simple technique, based on 45-deg-angled dry etching. This woodpile structure is composed of air columns (n=1) surrounded by Si (n=3.5). Band calculation based on the plane-wave method shows that the complete band gap is obtained for ℓ (width of column cross section) =0.4~0.6•(column period), when the column has a regular square cross section, even though the gap remains small. On the other hand, a large gap can be obtained for the rectangular cross section. The gap-midgap ratio exceeds 20% for the column cross section with a lateral- and vertical- width ratio of 2.4 (Fig. 1). We will also present a newly developed fabrication technique using an ICP deeply etching method [1].

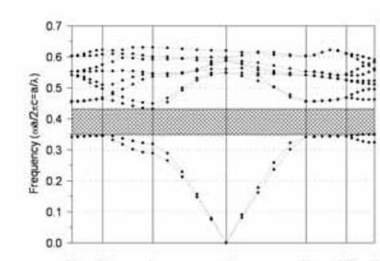


Fig. 1. Band structure for the column with a laterial- and vertical-width ratio of 2.4.

This work is supported by OITDA contracted with NEDO and MEXT IT Program.

[1] K. Hosomi et al., PECS-V, Mo-P1, p. 19 (2004).

Spectroscopic comprehensive studies of natural and synthetic opals

O. A. Kavtreva,A.V. Ankudinov,A.G.Bazhenova, A.A.Kaplyanskii,
Yu. A. Kumzerov, M. F. Limonov, and A. V. Sel'kin.
Ioffe Physico-Technical Institute, 194021, St.Petersburg, Russia.

Novel class of dielectric structures with a refractive index which exhibits spatially periodic modulation is known as photonic crystals. Photonic crystals do not occur naturally, except for a well-known gemstone natural opal with brilliance light scattering in the visible range. Both natural and synthetic opals are made up of closely packed uniformly sized SiO2 -spheres with diameter on the scale of a micrometer.

In the present work AFM and optical spectroscopic comparison studies of the both types of opals are carried out. We found Bragg diffraction spectral bands of the natural opals to be significantly narrower as compared to that of unfilled synthetic materials. Numerical calculations were performed within the model of a planar periodic layered medium making use of the transfer matrix technique, which indicate that the voids between SiO2 -spheres in the natural opals are filled with glass-like rock. From the spectra observed the information about real structure of synthetic opals has been extracted with an account of anisotropic shrinkage and sintering of SiO2 – spheres.

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Recent Developments of Photonic Crystal Polarizers

T. Kawashima[1], Y. Inoue[1], H. Abe[1], T. Sato[1], and S. Kawakami[1,2] 1) Photonic Lattice, Inc.,
2) Tohoku University, JAPAN.

Photonic crystal (PhC) polarizers are promising for many applications[1,2]: Small size, high performance (transmission >90% and high extinction ratio), etc. In this paper, we summarize recent topics of autocloned PhC polarizers. There are three keywords: Seamless coverage of the whole visible specrum by three (R, G, and B) polarizer chips; planar polarizer in the UV region (not known until now), and tolerance of the chip to high power lasers.

(1) R, G, B polarizer chips: For industrial applications such as liquid-crystal light valves in PC-connected projectors, inorganic power-tolerant polarizers are important. We have developed R, G, and B PhC polarizers satisfying industrial requirements. (2) UV operation: Performance down to λ= 285nm is confirmed. Details will be presented at the meeting. (3) Power tolerance: The chip was tested at 1064nm (CW and pulse) and 820nm (Femtosecond pulse). Details will be presented.

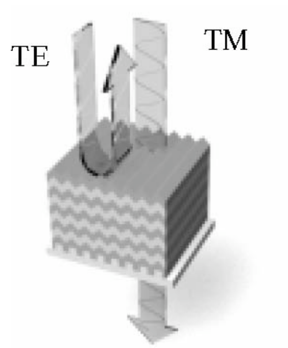


Fig. 1 PhC polarizer fabricated autocloning method. The devices for IR (λ= 1550 nm) [1] and for blue light (λ = 420-480 nm) [2] have been achieved.

[1] T. Kawashima et al., OFC, ThI2 (2003).

[2] T. Kawashima et al., PECS-V, Th-P31 (2004).

Terahertz photonic crystals fabricated by a high power femtosecond laser ablation technique

S. C. Choi, C.-S. Kee, Y. C. Noh, D.-K. Ko*, and J. Lee
Advanced Photonics Research Institute, Gwangju Institute of Science and Technology, Gwangju 500-712, Republic of Korea

Recent advances in generation and detection of terahertz (THz) waves are opening new technologies for Imaging, chemical detection, explosive Inspection, and so on [1]. The properties of photonic crystal such as photonic band gap can give an opportunity to improve the performance of THz sources and defectors. Furthermore, THz waveguides, filters and cavities based on photonic crystals could become important components for developing THz on-chip photonics. In this presentation, we show that micro optical machining using a high power femtosecond laser ablation technique can be suitable in the fabrication of THz planar photonic crystals. This technique requires simple processes and low-cost in comparison with a deep reactive ion etching technique that has been usually employed in micromachining of THz photonic crystals [2]. A square array of holes in a glass fabricated by the micro optical machining technique was shown Fig. 1. The period and hole size are easily controlled by varying position of microstage, laser spot size and power. The transmission spectra measured by scan fourier transform spectrometer equipped with a Si bolometer detector will be presented.

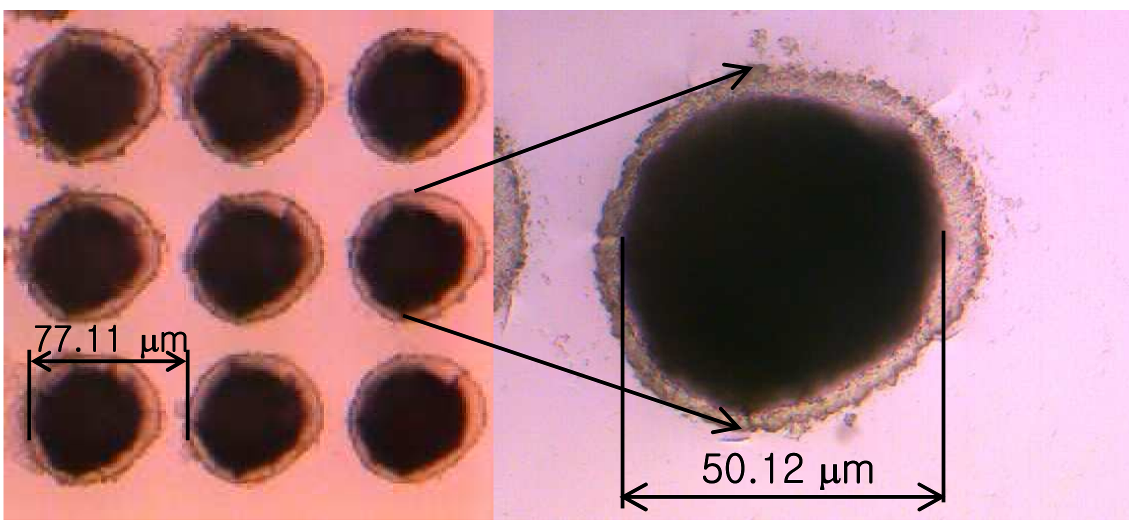


Figure 1. Microscope picture of square array of holes in a glass with thickness of 0.7 mm fabricated by a high power femtosecond laser ablation technique. The period of array is about 77 μm and the hole diameter about 50 μm.

Reference

*Email: dkko@gist.ac.kr

[1] X.-C. Zhang, *SPIE Lecture short course*, (2004).
[2] N. Jukam and M. S. Sherwin, *Applied Physics Letters*, **83**, 21 (2003)

Dependence of supercontinuum spectra generated in photonic crystal fibers on polarization direction of incident femtosecond laser pulse

H.-G. Choi, T. J. Yu*, C.-S. Kee, D.-K. Ko, and J. Lee
Advanced Photonics Research Institute, Gwangju Institute of Science and Technology, Gwangju 500-712, Republic of Korea

Supercontiuum (SC) generation using ultrashort laser pulses has found very useful in spectroscopy, optical coherent tomography, optical frequency metrology, and so on [1]. In recent, there have been many works on generating SC spectra using photonic crystal fibers (PCFS) with high nonlinearity and zero dispersion [2]. The previous works reported the dependence of SC spectra on the peak power and the pulse length of pumping source, and the dispersion of PCF for the pumping wavelength. In this presentation, we report the dependence of SC spectra on the angle between the polarization direction of incident femtosecond laser pulse and the principal axis of PCF employed in the experiment. The measured results indicate that the SC spectra are sensitive to the angle. This is probably due to the complicated core and cladding structures of PCF. The detail analysis of the correlation between the angle dependent SC spectra and the structures should be presented.

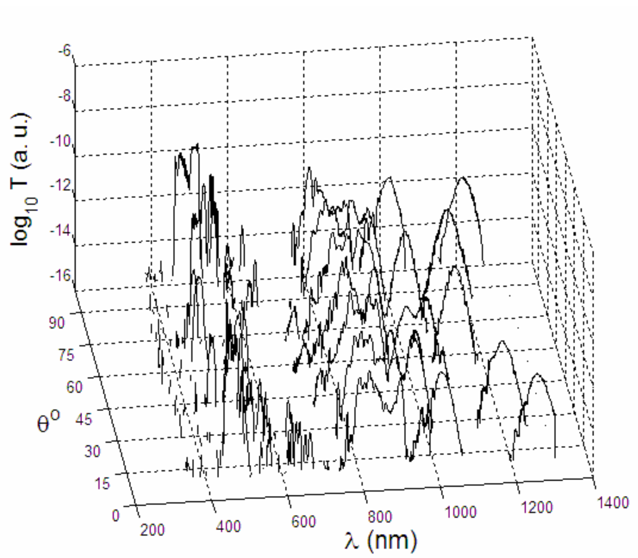


Figure 1. Measured SC spectra as a function of angle θ^o between the polarization direction of pumping pulse and the principal axis of nonlinear polarization maintaining PCF with zero dispersion wavelength of 750 nm (NL PM 750; CRYSTAL FIBRE). The pulse length and the wavelength of pumping pulse are about 100 fs and 830 nm, respectively.

Reference

*Email: tjyu@gist.ac.kr

[1] R. R. Alfano, The *Supercontinuum Laser Source* (Springer-Verlag, New York, 1989).
[2] J. C. Knight, *Nature* (London), 809, 847 (2003).
[3] M. Lehtonen, G. Genty, H. Ludvigen, and M. Kaivola, *Applied Physics Letters*, **82**, 651, (2003).

Experimental study of elastic band gaps in a three-dimensional ultrasonic crystal

A.Khelif, A. Choujaa, S. Benchabane, and V. Laude,
Département LPMO, Institut FEMTO-ST, 32 avenue de l'Observatoire, F-25044 Besançon cedex, France.

A great deal of research effort is currently being devoted to the study of acoustic or elastic waves propagation in periodically structured materials, such as the so-called phononic crystals. These are made of two-or three dimensional periodic repetitions of different solids or fluids which exhibit absolute stop bands in the transmission spectrum of acoustic waves. The location and width of these band gaps result from a large contrast in the value of elastic constants and/or mass density of the constitutive materials.

In this work, we report on the experimental observation of the existence of a full acoustic band gap in a three dimensional crystal, consisting of fcc arrays of close-packed steel beads in epoxy matrix. The choice of steel and epoxy as the composite materials is based on the strong contrast in their densities and elastic constants. The scatterers diameter is 4 mm and the filling fraction of the close-packed lattice is 74 %. For this arrangement, we measure a huge full band-gap extending between 300 kHz and 650 kHz (60% fractional bandwidth) in which elastic waves are not allowed to propagate in all directions. This makes this structure a potential candidate for designing new acoustic filters or insulators.

Photonic band gaps in highly conformal shell structures

D. Gaillot, T. Yamashita and C.J. Summers
School of Materials Science & Engineering
Georgia Institute of Technology, Atlanta, GA-30332-0245, USA

Large 3D photonic band gap (PBG) materials offer revolutionary advances in controlling spontaneous emission rate and Anderson localization. Nevertheless, current techniques are not yet adequate to fabricate large area structures with optimum photonic properties. Inverse shell opals offer a bottom-up approach to fabrication but are limited by the small PBG and the lack of appropriate materials for operation in the visible where most impact is expected. We report theoretical investigations of the gap width and minimum refractive index contrast required to open a complete PBG for inverse shell opal derivatives. Backfilled geometries, achieved by growing a high refractive index material conformally on the interior surfaces of inverse shell opals, using techniques such as atomic layer deposition, are presented. A highly conformal silicon inverse non-close-packed opal that exhibits a complete PBG of 7.2% is predicted compared to 2.6% for an 86% conformally coated inverse shell opal. Also, our simulations indicate a complete PBG is sustained for refractive indices greater than 2.9 compared to 3.3. Furthermore, it is predicted that for a theoretical structure in which, prior to backfilling, 97.7% of the interstitial volume is conformally coated, should support a 16% complete PBG and a lower refractive index requirement of 2.55. These novel PBG structures would allow operation in the visible using lower refractive index materials.

Effective Index Model for Propagation through Photonic Crystals

T. Yamashita and C. J. Summers,
Georgia Institute of Technology, School of Mat. Sci. & Eng., Atlanta, GA, 30332, USA

Through the control of material properties on the same size order as the wavelength of light, photonic crystals offer unique phenomena unavailable in conventional optical materials. The ability to tune the band structure of a photonic crystal through the shape, size, and the properties of its constituent parts allows the design of metamaterials with controlled anisotropy and sensitivities to frequency. Various researchers have modeled the propagation in different regimes of the photonic band structure, but limitations have prevented the application of these models to cover the large range of phenomena simulated today. This study develops an effective index model for photonic crystals that accounts for both the amplitude and the phase of light propagation. The band structure, calculated through the plane wave expansion method, is fit to models of anisotropic crystals. The results are applied to model the behavior of light in photonic crystals exhibiting negative index, superprism, and self-collimation behavior. Good agreement is found between the model and the propagation properties of Gaussian beams in photonic crystals. The development of a complete theory is essential to systematically design complex systems utilizing photonic crystal devices, such as negative index lenses, superprism based DWDM devices, and self collimation based micro-filters and waveguides.

Comprehensions on side-coupling characteristics of cavities and waveguides in triangular-lattice photonic-crystal slabs

Guk-Hyun Kim and Yong-Hee Lee
Department of Physics, KAIST, Daejeon 305-701, Korea

The side-coupling between a cavity and a waveguide is an important geometric configuration to construct photonic-crystal-based optical circuits. Using the FDTD method, we investigated side-coupling characteristics between Γ-K directional waveguide modes and various resonant cavity modes in a triangular-lattice photonic-crystal slab. To understand the coupling characteristics systematically, we classified the side-couplings into three following cases based on relative field distributions of cavity and waveguide modes. (1) The cavity mode is donor-type and its decaying Γ-M direction is perpendicular to the waveguide axis (Fig. 1). (2) The decaying Γ-M direction of donor-type mode is not perpendicular to the waveguide axis (Fig. 2). (3) The cavity mode is acceptor-type (Fig. 3). In each case, the coupling characteristics were well described by the simple argument of transverse overlap between cavity and waveguide modes over the waveguide region. We will show the coupling characteristics and the corresponding arguments for various side-couplings. The classification and transverse-overlap argument would be a useful tool to design cavity-waveguide coupled structures in photonic crystals.

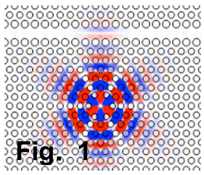


Fig. 1

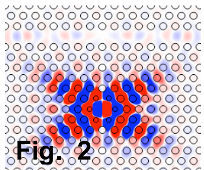


Fig. 2

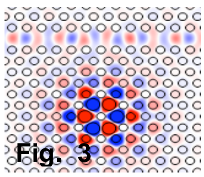


Fig. 3

Photonic crystal based higher-order bandpass filter design for WDM communication systems

Dongsoo Park, Sangin Kim, Ikmo Park, and Hanjo Lim,
School of Electrical and Computer Engineering, Ajou Univ., Suwon 443-749, Korea.

We report on the design of higher-order filter based on coupled defects In photonic crystals. The designed filters consist of coupled point defect resonators embedded in two-dimensional photonic crystal waveguide.

The coupling between defect resonators has been modeled using the coupled mode theory In time [1], and the general method to compensate for the arbitrary phase shift effect In the coupling has been Investigated. The designed filter shows a flat pass band of 50GHz and 0.3 dB in-band ripple, which is suitable for typical WDM communication systems with 100GHz channel spacing as seen in Fig. 1. The performance of the filter has been calculated using finite-difference time-domain method.

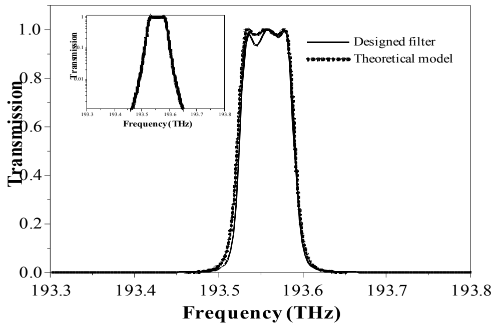


Fig. 1 Transmission of the designed photonic crystal based third-order filter

[1] H. A. Haus, and Y. Lai, *IEEE J. Quantum Electron.*, **28**, 205 (1992).

Localization behavior of electromagnetic wave in three-dimensional photonic fractals

S. Kirihara and Y. Miyamoto Joining and Welding Research Institute, Osaka University 11-1 Mihogaoka Ibaraki, Osaka 567-0047, Japan

M. W. Takeda and K. Honda Faculty of Science, Shinshu University 3-1-1 Asahi Matsumoto, Nagano 390-8621, Japan

K. Sakoda Nanomaterials Laboratory, National Institute for Materials Science 3-13 Sakura, Tsukuba, Ibaraki 305-0003, Japan

Three-dimensional photonic fractals with the self-similar pattern of dielectric media can localize strongly electromagnetic waves. We have fabricated various 3D photonic fractals with Menger-sponge structure composed of epoxy with titania-silica particles dispersion using stereolithography of a CAD/CAM system. Menger-sponge structures have the cubic body with the cube size a and square through-holes with the edge sizes of a/3, a/32, a/33,.depending on the stage number. When the cube size is 81mm, the localized frequencies measured by using network analyzer and two horn antennas were 9.5, 10.5, 12.0 and 13.5 GHz for stage 1, 2, 3, and 4, respectively. These localized frequencies showed good agreements with the calculated ones using an empirical equation, which we derived to predict the localized wavelength as functions of the cube size, stage number, volumetric mean dielectric constant, and order number of a localized mode. The intensity profiles of electric field measured at the inner and outer air space of Menger sponge fractals with the stage number over 2 confirmed the complete confinement of the wave energy. When the cubic symmetry was broaken by introducing small distorsions or tetragonality, or by filling some square holes with the same media, broadning, splitting, and quenching of localized modes occurred. These interesting localization behaviors of electromagnetic waves in photonic fractals with Menger sponge structures and their modified structures will be reported.

Effect of 2D photonic crystal slab with C_{3v} symmetry on introduction of asymmetry for the vertical direction

Hitoshi Kitagawa[*1,2], Yoshinori Tanaka[*1], Takashi Asano[*1] and Susumu Noda[*1],
[*1]Dpt. of Electronic Science and Engineering, Kyoto Univ., Kyoto 616-8510, Japan,
[*2]Dvlp. Cent. ALPS Electric Co., Ltd., Sendai, 981-3208, Japan.

We previously proposed a photonic crystal (PC) slab with C_{3v} symmetry in a triangular lattice, which has 2D complete photonic bandgap[1]. In this symposium, we report on a concrete example of the merit of this structure. In the case of conventional PC slab with circular air holes, when an asymmetry for vertical direction is introduced (see Fig.1(a)), TE-TM mode conversion occurs and Q factors of the cavities formed in PC slab are degraded (see solid circles in Fig.2.). [Note that shallow holes are expected to improve the pattern of radiation from the cavity to the free space[2]]. On the other hand, when we employ C_{3v} symmetry (see Fig.1(b)), Q factors are found not to degraded (see solid triangles in Fig.2.).

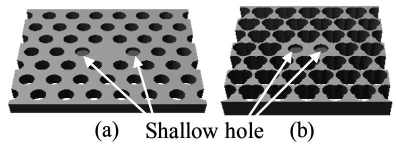


Fig.1. Two types of 2D PC slabs with a nanocavity. Shallow holes produce vertical asymmetry.

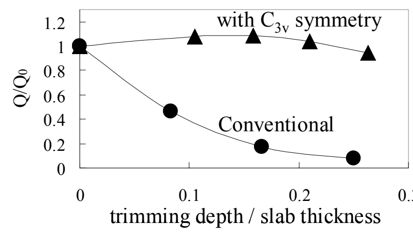


Fig.2. Variation of Q factors as a function of trimming depth of shallow holes. Q_0 is bare Q factor.

[1] H. Kitagawa, T. Asano and S. Noda, PECS-V, March, 22 (2004).
[2] Y. Tanaka, et al., 3p-ZC-2, the 65th Autumn Meeting,JSAP (2004).

Transmission characteristics of the coupled 1D photonic crystal

H. Kitahara and M. Hangyo
M. W. Takeda,
Institute of Laser Engineering Osaka University, 3F 21st Plaza 2-6, Yamadaoka, Suita, Osaka, Japan.
Department of Physics, Faculty of Science, Shinshu University, 3-1 Asahi, Matsumoto, Nagano, Japan.

General photonic crystals, that are made of the bulk material such as dielectrics, can not interact strongly with the other photonic crystals even if they are in contact with the surface of themselves. But a pair of stripline photonic crystal (SPC) [1,2] can couple strongly by placing them closely [3], because the SPC can couple by using their whole crystal. Therefore, we can consider about a strongly coupled system of the photonic crystal. Figure 1 shows the structure of the coupled SPC studied in this paper.

We investigated the transmission and reflection characteristics of the coupled SPC. The transmission characteristics was calculated by using the Method of Moment (MoM). The SPC were made of copper foil embedded in the teflon substrate. Two striplines are not in contact with each other, but it overlaps on a 0.127mm interval at the center of the SPC. Figure 2 shows the simulation result of transmission and reflection characteristics. The solid line (P1-P1) is a reflection spectrum of port 1 (P1). The dashed line (P1-P4) is a transmission spectrum of port 4 (P4). The electromagnetic wave is sent from P1. Peak and dip frequencies of the first band in the transmission correspond to those frequencies in the reflection. Therefore the reflection characteristics (P1-P1) was contained in the transmission spectrum (P1-P4). The numerical analysis and the result of observation will be reported at the presentation.

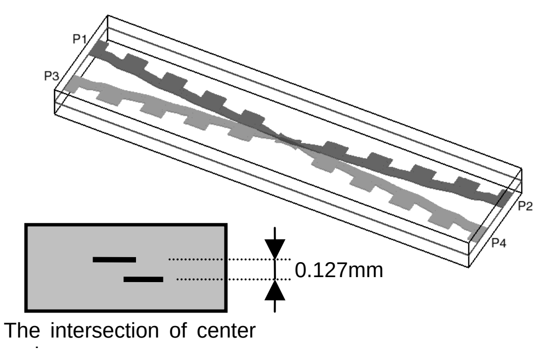


Fig.1. Coupled stripline photonic crystal (SPC).

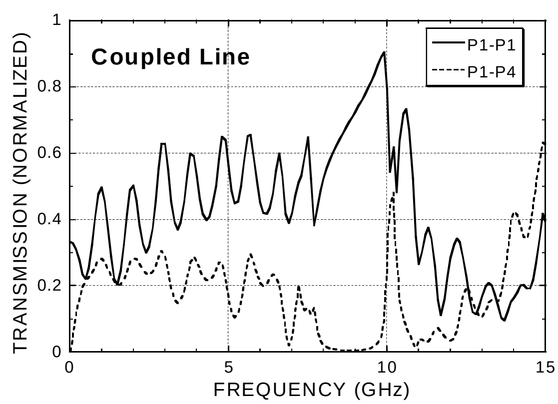


Fig.2. Calculated transmission characteristics of coupled SPC.

[1] F. Falcone, T. Lopetegi, M. Irisarri, M. A. G. Laso, M. J. Erro, and M. Sorolla, *Microwave and Optical Technology Letters*, **23**, 223 (1999).
[2] H. Kitahara, T. Kawaguchi, J. Miyashita, and M. W. Takeda, *Journal of the Physical Society of Japan*, **72**, 951 (2003).
[3] H. Howe, *Stripline Circuit Design*, Artech Hous, 153 (1974).

Nonlinear control of directed emissions from photonic crystal waveguides

Steven K. Morrison and Yuri S. Kivshar
Nonlinear Physics Centre, and Centre for Ultra-high Bandwidth Devices for Optical Systems (CUDOS), Research School of Physical Sciences and Engineering
Australian National University, Canberra ACT 0200, Australia

The beaming effect of light is of great practical importance for achieving the efficient emission of light from subwavelength apertures. In this case, light exiting the aperture is focused into a narrow directed beam in front of the aperture, via coherent interference of radiated surface modes. This effect, enhanced through the periodic corrugation of the exit surfaces in metallic thin films and photonic crystals, can be employed to produce nanofocusing of light, which may provide great benefits for near-field optical devices working below the diffraction limit. Here, we extend the theory of the beaming effect in photonic crystals to include dynamic, all-optical control of the directed emission, leading to an effective free-space switching of light. We illustrate this effect using the transmission from a photonic crystal waveguide formed in a truncated crystal, and incorporating a nonlinear surface structure that provides intensity dependent control over the directed emission of light. We show that the dynamic control over the transmitted light can be achieved at moderate power levels as a result of the slow group velocity of the light within the surface modes combined with a strong localization of light within the photonic crystal structure near the waveguide exit.

Guiding light between pillars in InP-based photonic crystals

A.A.M. Kok, E.J. Geluk, J.J.G.M. van der Tol, F. Karouta, Y.S. Oei, M.K. Smit
COBRA Research Institute, Eindhoven University of Technology,
PO Box 513, 5600 MB Eindhoven, The Netherlands

Photonic crystals can significantly reduce the size of components in integrated optical circuits. Furthermore, they can add new functionalities to these circuits. In a two-dimensional photonic crystal waveguide, light is confined in-plane by the photonic band gap, and in the third dimension by an index contrast. For a photonic crystal consisting of pillars, which shows a large TM band gap [1], the out-of-plane confinement is weak due to a lack of guiding between the rods.

We aim for fabrication of photonic crystal devices based on pillars of InP with a guiding layer of InGaAsP. Scattering losses due to side wall roughness are reduced by applying a polymer between the pillars [2]. However, this does not solve the problem of the weak out-of-plane confinement. We propose to realize additional guiding between the pillars by implementing a three-layer polymer structure, which will reduce the waveguide losses even more. The index contrast and the thickness of the polymer layers should be matched to those of the pillars.

We present our first technological tests and simulations, showing the feasibility of combining a two-dimensional InP-based photonic crystal of pillars with a three-layer polymer stack to improve the guiding of light.

[1] J.D. Joannopoulos, R.D. Meade, and J.N. Winn, *Photonic crystals: molding the flow of light* (Princeton University press, Princeton, 1995).

[2] M. Tokushima, H. Hirohito, and Y. Arakawa, *Appl. Phys. Lett.*, **84**, 21 (2004).

Self-organized micro-structures of $PrAlO_3/Al_2O_3$ and $PrAlO_3/Pr_2O_3$

D. A. Pawlak, K. Kolodziejak, J. Kisielewski, T. Lukasiewicz, M. Malinowski, M. Kaczkan
D. A. Pawlak/Institute of Electronic Materials Technology, ul. Wolczynska 133, 01-919 Warsaw, Poland.

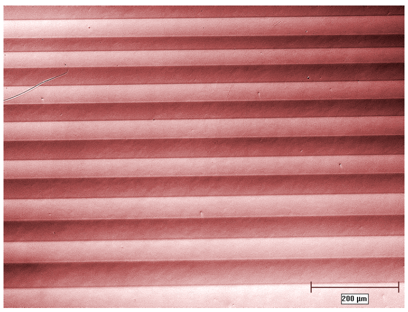


Fig. 1. Optical microscope image of the microtwin domains in $PrAlO_3$ single crystal.

The self-organized dielectric micro-structures of $PrAlO_3/Al_2O_3$ and $PrAlO_3/Pr_2O_3$ will be presented. Their growth is based on directional solidification of binary eutectics by the micro-pulling down method. The microstructure will be compared with the microstructure of pseudo-periodic twin domains in $PrAlO_3$ crystal grown by the Czochralski method, Fig. 1. One of the phases can be etched away selectively. The empty spaces could be filled with a metal giving the possibilities of using these structures as kind of metamaterials. The spectroscopic properties of the microstructures will be presented.

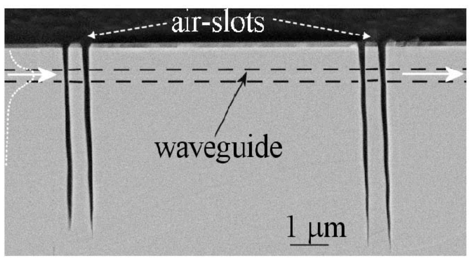
[1] D. A. Pawlak, T. Lukasiewicz, M. Carpenter, M. Malinowski, R. Diduszko, J. Kisielewski, submitted to J. Cryst. Growth

Compact Multiquantum-well tunable filters in InP

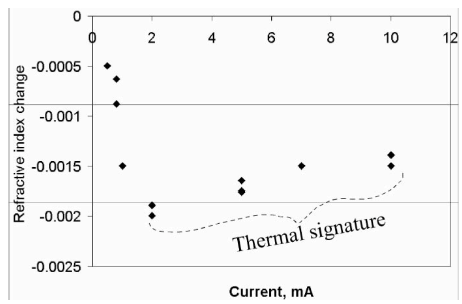
M. V. Kotlyar, L. O'Faolain, A. Krysa and T. F. Krauss,
School of Physics and Astronomy, Univ of St Andrews, St Andrews, Fife, UK.

We present experimental results for compact (20-40µm) electro-optically tuned Fabry-Perot filters in InGaAsP/InGaAsP Multiquantum-well material. Deeply etched 1-D photonic crystals [1] were used to create high reflectivity mirrors on both sides of the Fabry-Perot cavity (Fig. 1 a). Both carrier-injection and the quantum confined Stark effect were implemented to achieve tunability. Red and blue-shifts of the transmission peaks of order 1-2nm for both effects were experimentally observed. The signature of the thermo-optic effect opposing the carrier-injection induced blue-shifts was clearly demonstrated (Fig. 1 b).

[1] M. V. Kotlyar, L. O'Faolain, R. Wilson and T. F. Krauss, *JVST(B)*, **22**, 1788 (2004).



a)



b)

Fig.1. a) SEM image of the cross-section of the device, b) modal refractive index changes induced in a 40-µm cavity by carrier-injection

Lasing in perfect and disordered photonic quasi-crystals

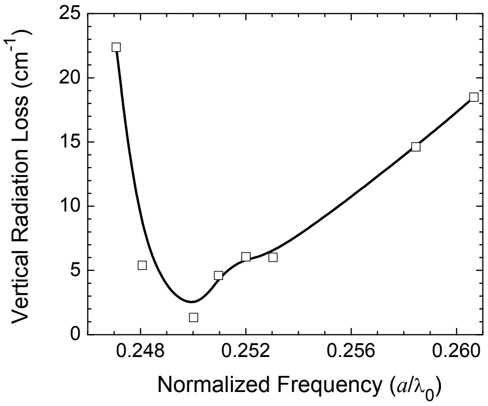
D. N. Chigrin, and J. Kroha Institute of Physics, University of Bonn, Nussallee 12, D-53115 Bonn, Germany

Photonic quasi-crystals are artificial dielectric inhomogeneous media, where scattering centers are located in the vertices of a quasi-periodic tiling of space. The eigenstates of quasi-crystals are critical: they are neither singular nor continuous. The criticality of the eigenstates of quasi-periodic structures has a major implication on light propagation and emission processes. Photonic quasi-crystals are unique optical materials, which can support both localized and extended standing waves in a defect-free lattice. That puts quasi-crystals by their optical properties between perfect periodic and strongly disordered materials. A laser is generally comprised of two components, a laser active medium, in which level population inversion can be achieved by pumping, and an optical element (resonator, periodic lattice, etc.), which provides necessary feedback to stimulate emission. Both localized and extended standing eigenstates can provide a necessary feedback to achieve lasing in a defect-free quasi-crystal. In this contribution, we study lasing action in perfect and disordered octagonal photonic quasi-crystal. An influence of transition from a perfect quasi-periodic structure to a disordered one on lasing properties is systematically addressed. Numerical calculations are performed using finite-difference time-domain method. Active media is modeled by the semi-classical laser equations. Because such a model couples electronic number equations at different levels with field equations, the amplification is non-linear and saturated, so stable state solution can be obtained after a long relaxation time.

Predicted Low-Loss Photonic Crystal Waveguides in SOI

Wan Kuang, Adam Mock, and John D. O'Brien
PHE 431, Electrical Engineering – Electrophysics, University of Southern California, Los Angeles, CA 90089, U. S. A.

We have numerically demonstrated [1] that vertical radiation loss of photonic crystal waveguides on high index substrates can be reduced by shifting one side of the cladding along the direction of the waveguide by half of a lattice period, which is generally referred to as a type-B waveguide [1, 2]. In this summary, we improve over the structure by minimizing the dry etching depth to less than 1 micron. The waveguides modeled here were formed by indices of refraction consistent with a Si/SiO_2 waveguide with normalized thicknesses of 0.6 and 4.0.



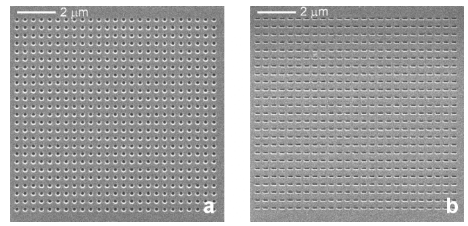
A type-B photonic crystal waveguide eliminates the Fourier component of the photonic crystal lattice along the Gamma-Kappa axis, and reduces its magnitude for locations nearby. This leads to a reduction in the predicted radiation loss.

Fig. 1 shows the vertical radiation loss calculated with a three-dimensional finite-difference time domain method detailed in [2]. The minimum radiation loss is predicted to be 1 cm^{-1} and a bandwidth of 32 nm for loss of 5 cm^{-1} for a lattice constant, a, of 390 nm. This is more than an order of magnitude reduction in radiation loss compared to the type-A structure. In addition, this loss is a result of a photonic crystal geometry in which the holes of the lattice only need to be etched 780 nm deep.

[1] Wan Kuang and John D. O'Brien, *Reducing the out-of-plane radiation loss of photonic crystal waveguides on high-index substrates*, Optics Letters, **29**, 860 (2004)
[2] H. Benisty, *Modal analysis of optical guides with two-dimensional photonic band-gap boundaries*, J. Appl. Phys. **79**, 7483 (1996)
[2] Wan Kuang, C. Kim, A. Stapleton, W. J. Kim, and J. D. O'Brien, *Calculated out-of-plane transmission loss for photonic crystal slab waveguides*, Optics Lett., **28**, 1781 (2003)

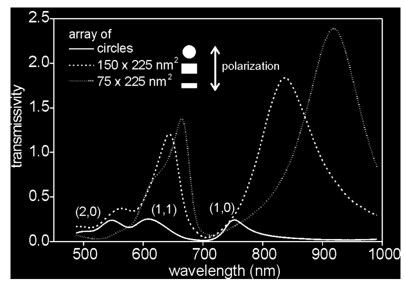
Modifying the properties of plasmonic crystals through engineering of the primitive unit cell

L. Kuipers[1,2], K.L. van der Molen[2], K.J. Klein Koerkamp[2], F.B. Segerink[2], N.F. van Hulst[2], S. Enoch[3]
[1] FOM Institute for Atomic and Molecular Physics, Amsterdam, The Netherlands
[2] MESA+ Institute for Nanotechnology, University of Twente, Enschede, The Netherlands
[3] Institut Fresnel, Marseille, France



Extraordinary transmission, first observed by Ebbesen and co-workers, is one of the most beautiful phenomena in plasmonic crystals. This transmission has generally been attributed to a resonant excitation of surface plasmons set up by the periodicity of the array. *Here, we will show that this explanation cannot be the entire story.*

Contrary to expectations, by changing the shape of the sub-wavelength holes and thus engineering the primitive unit cell, we are able to enhance and, more importantly, change the peak positions.



[1] K.J. Klein Koerkamp, et al., *Phys. Rev. Lett.* **92**, 183901 (2004).
[2] K.L. van der Molen, et al., *Appl. Phys. Lett.* **85**, 4316 (2004).

Optical Properties of Photonic Crystal Slab Components: Role of Disorder

E. Kuramochi, M. Notomi, S. Hughes, G. Kira*, L. Ramunno**, A. Shinya, and T. Watanabe
NTT Corporation, 3-1 Morinosato Wakamiya, Atsugi, 243-0198 Japan.

*Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama, 226-8502 Japan.
**Univ. of Ottawa, Ottawa, Canada.

We study the effect of structural disorder for propagation loss of waveguides and quality-factor (Q) of cavities in photonic crystal slab (PCS). We report here our recent achievement of very low propagation loss (2dB/cm) for W1 waveguides as a result of reduction of fabrication disorder, and we also study this disorder-induced scattering problem by a theoretical formalism using photon Green function [1], and compare between experiment and theory, which clarifies the physical mechanism of scattering loss in fabricated PCS waveguides [2]. Furthermore, we study disorder-induced scattering effects on Q for PCS cavities. Our numerical analysis demonstrates that Q of PCS nanocavity is decreased substantially by hole-size disorder.

[1] S. Hughes et al., *Phys. Rev. Lett.*, **94**, 033903 (2005).
[2] E. Kuramochi et al., Submitted for publication.

Electroluminescent three-dimensional photonic crystals based on opal-Zn_2SiO_4:Mn and opal-GaN-ZnS:Mn composites

D.A. Kurdyukov, S.F. Kaplan, N.F. Kartenko, A.V. Medvedev, and V.G. Golubev,
Ioffe Physico-Technical Institute, Russian Academy of Sciences, Politekhnicheskaya 26,
St. Petersburg, 194021, Russia.

Electroluminescent three-dimensional photonic crystal (PC) structures based on opal-Zn_2SiO_4:Mn and opal-GaN-ZnS:Mn composites have been fabricated for the first time. The opal-phosphor composites were synthesized by chemical bath deposition technique. The crystal structure of the composites synthesized was investigated by the powder X-ray diffraction method. Electroluminescent structures were made from synthesized composites by depositing a conductive semitransparent indium-tin oxide (ITO) layer on one PC facet and a layer of $BaTiO_3$ powder dispersed in an organic compound on another, followed by deposition of a silver paste layer. Electroluminescence (EL) was excited by an alternating current electric field, whose characteristics were well below the breakdown threshold (strength ~10^4-10^5 V/cm, frequency ~0.1-2 kHz). The composites synthesized have been found to demonstrate an effective EL comparable with commercially produced phosphors both in green (opal-Zn_2SiO_4:Mn) and yellow (opal-GaN-ZnS:Mn) spectral ranges.

The photonic bandgap properties of the opal-phosphor composites have been studied by measuring angular resolved Bragg reflection spectra from the (111) surface of the PCs. The registration of the reflection spectrum was followed by recording the EL spectrum from the same place of the sample. Both spectra were measured through the ITO film from the surface regions of 2×2 mm in size. The EL spectrum was founded to be considerably modified by the photonic band gap (PBG) to become anisotropic in accordance with the PBG angular dispersion.

The results demonstrated show the opportunity to control flow of light in conventional light-emitting devices and open the way to create PBG-governed optoelectronic structures.

The support of Russian Academy of Sciences and the EC-funded projects PHOREMOST (FP6/2003/IST/2-511616) is gratefully acknowledged.

Boundary element analysis for metal-clad plasmon resonators

Yoichi Kurokawa[1] and Hideki T. Miyazaki[2]

[1]International Center for Young Scientists, National Institute for Materials Science,
1-1 Namiki, Tsukuba, Ibaraki 305-0044, Japan.
Email: KUROKAWA.Yoichi@nims.go.jp
[2]Materials Engineering Laboratory, National Institute for Materials Science,
1-2-1 Sengen, Tsukuba, Ibaraki 305-0047, Japan.

Recently, extraordinary transmission through subwavelength apertures in metal films is attracting attention.[1)] In particular, the effect of shape and size of apertures is of great interest. We are investigating the optical properties of an infinite slit in a Drude material film by use of the boundary element method. This method is chosen, since this is more convenient to model small structures, compared with FDTD method. When a TM-polarized light is incident on the slit, dips in addition to peaks appear in the transmission spectra. These are due to the Fabry-Perot resonance of the propagation mode of a metal-clad waveguide[2)] by the reflection at the entrance and the exit surfaces. The existence of the dips by the resonance is a unique feature for Drude materials. For a perfect conductor, all resonances yield transmission peaks.[3)]

[1] T. W. Ebbesen et al., Nature (London) **391**, 667 (1998). [2] E. N. Economou, Phys. Rev. **182**, 539(1969). [3] Y. Takakura, Phys. Rev. Lett. **86**, 5601(2001).

Highly directional vertical emission from heterogeneous photonic crystal cavity with elliptical air holes

Soon-Hong Kwon, Sun-Kyung Kim, Se-Heon Kim, and Yong-Hee Lee
Department of Physics, KAIST, Taejon 305-701, Korea

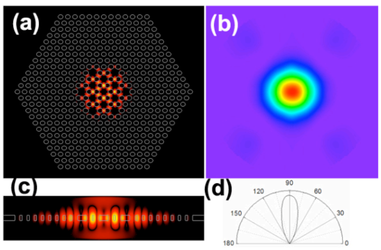


Fig.1 (a) Top view and (c) side view of calculated mode pattern. (b) Far-field image. The center corresponds to the vertical direction. (d) radiation profile.

The emission from photonic crystal (PC) cavity tends to spread over broad angle. Therefore, it is crucial to control radiation patterns of PC cavity mode in order to realize highly directional light source for add/drop filter [1]. As a candidate of the vertical emitters, we chose the resonant mode whose x- or y-directional electric field has even mirror symmetry for both axes and both electric fields are cancelled out along the vertical direction. Through the elongation of air holes of PC, we broke the cancellation condition of the electric field such that vertical emission is allowed. Furthermore, in order to obtain narrow divergence angle, we introduced graphite lattices inside the triangular lattice. Here, a graphite lattice can be considered as a two-dimensional (2D) array of single-cell cavities. The coherent coupling of 2D arrayed cavities enable the reduction of the divergence angle as the number of graphite lattice increases.

[1] T. Asano, B. S. Song, Y. Tanaka, S. Noda, *Appl. Phys. Lett.*, **83**, 407 (2003)